GEOGRAPHICAL VARIATION IN SITKA SPRUCE PRODUCTIVITY AND ITS DEPENDENCE ON ENVIRONMENTAL FACTORS.

BY

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ABSTRACT

The objective of this study was to investigate altitudinal and geographical variation in the productivity of Sitka spruce in upland Scotland, to relate this to environmental variables and to use the information to develop a basis for predicting Sitka spruce yield from site factors.

A total of 188 0.04 ha temporary sample plots were established in 15 to 50 year old Sitka spruce stands at 37 sites in Scotland and northern England, mostly spanning the upper 200 m elevation range of plantations. At each plot estimates of General Yield Class (GYC) were made and the following site factors were assessed; elevation, geomorphic shelter (topex), aspect, slope, soil type and rooting depth. In addition, estimates of wind-climate, mean summer temperature (June - September), mean annual accumulated temperature > 5.6 °C and annual rainfall were made by extrapolation of Forestry Commission "tatter flag" records and Meteorological Office data.

GYC declined by about 3.2 - 4.0 $m^3ha^{-1}yr^{-1}$ per 100 m increase in elevation due to the effects of increasingly adverse climatic and edaphic conditions. GYC was fairly closely correlated with elevation at the individual sites, but there was considerable site to site variation. GYC values at specific elevations were higher in inland and southern areas than in coastal and northern ones. The geographical pattern of the relationship between GYC and elevation was strikingly similar to the distributions of growing season temperatures and wind-climate.

Correlation and multiple regression analysis demonstrated that GYC was well correlated with extrapolated values of accumulated temperature and tatter rate, these two variables accounting for up to 78 per cent of the variation in GYC in the best multiple regression models. GYC also proved to be correlated with aspect, topex, soil type and crop age. Productivity was highest on north and east-facing aspects and increased with greater levels of geomorphic shelter. Differences in soil type only accounted for a small amount of variation in GYC (2-3 per cent). GYC was significantly negatively correlated with crop age, probably as a result of improved standards of silvicultural treatment.

The best multiple regression models accounted for 78-86 per cent of the variation in GYC and were associated with confidence limits of ± 2.2 - 2.6

$m^3ha^{-1}yr^{-1}$. The mean error for predicting GYC for a single site (acquisition) was calculated to be ±1 $m^3ha^{-1}yr^{-1}$, and this figure was confirmed by results of a validation survey. The information presented could easily be adapted for predicting productivity and assessing suitable upper planting limits in practical forestry.

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Acc temp	Mean annual accumulated temperature
Acc temp SL	Mean annual accumulated temperature adjusted to sea-level
Asp	Angle of aspect
BB	Basin bog
BE	Brown earth
CL	Confidence limit
Coeff	Coefficient
Cos	Cosine
df	Degrees of freedom
Elev, Elevatn	Elevation
FP	Flushed peat
Grid ref	Grid reference
GYC	General Yield Class
H/D	Height to diameter ratio of top height trees
IP	Ironpan
LYC	Local Yield Class
PCA	Principal component analysis
PG	Peaty gley
Pod	Podsol
PWD	Potential water deficit
RD, Root D	Rooting depth
RMS	Residual mean square
S-L, SL	Sea-level
Sin	Sine
Summ temp	Mean temperature of four warmest months
Summ temp SL	Mean temperature of four warmest months adjusted to sea-level
SS	Sum of squares
SWG	Surface water gley
Tatt	Tatter rate
Tatt SL	Tatter rate adjusted to sea-level
Tem, temp	Temperature
Top	Topex
Tot D	Total soil depth
UP	Unflushed peat
WZ	Windzone

CHAPTER 1

INTRODUCTION

Afforestation in Great Britain has largely taken place in upland areas between about 200 and 500 metres above sea-level. Lower limits to the expansion of forestry have generally been set as the result of competition with agriculture and upper limits (planting limits) by the effects of adverse climatic and soil conditions. This zone accounts for about 40 per cent of the total land area of Scotland (Halstead 1973) and about 75 per cent of the area of land planted in Scotland by the Forestry Commission (Lines 1973, M. Locke pers. comm.). The effects of climatic and soil conditions on tree growth in upland areas are only poorly understood, particularly on more exposed sites near the planting limit.

An understanding of the effects of the upland environment on tree growth is essential as a basis for the prediction of timber yields and the accurate assessment of planting limits. Prediction of the productivity of forest land has become increasingly important in various aspects of forest management. These include land acquisition and investment decisions, choosing appropriate silvicultural and management practices, production forecasting and land use planning. The need for more detailed knowledge of the likely levels of productivity is ultimately linked with the fact that forestry has become increasingly subject to the same sorts of financial and fiscal controls as other commercial enterprises.

Detailed information about tree growth has become of particular importance as forestry has advanced onto progressively more extreme sites. This steady advance is largely a reflection both of pressures in the market for land and of modern advances in site amelioration techniques. The degree to which soil conditions can now be improved has resulted in afforestation being pushed upwards towards its climatic limits. For this reason definition of upper planting limits has become particularly relevant.

This thesis attempts to develop a basis for predicting the productivity of Sitka spruce (*Picea sitchensis* Bong.Carr) in upland areas of Scotland and northern England, particularly on exposed sites. Investigation of the effect of increasing elevation on productivity and the dependence of this relationship on meteorological factors, was given particular prominence.

1.1 Site and productivity investigations in upland forestry in Britain.

1.1.1 Historical context

Zehetmayr (1954, 1960) describes early afforestation schemes undertaken on upland heaths and peats in Scotland and Ireland in the period 1730 to 1919. These early plantations were established using a minimum of cultivation but despite this productive stands were reported at elevations as high as 500 m above sea-level (Guillebaud and MacDonald 1928). Probably the most notable and successful of these schemes was at Corrour in Inverness-shire in which 240 ha of land at elevations between 400 and 500 m above sea-level were planted beginning in 1892 (Stirling-Maxwell 1907). The total upland area afforested before 1919 remained small but such plantations provide a valuable indication of the potential of upland areas for further afforestation.

Prior to 1919 afforestation in Britain had taken place with an "almost complete lack of accurate information about the rate of timber production" (Forestry Commission 1920). The same report states that:

> "very little is known about the effect of various factors of locality on the growth of ......trees" and that it was "impossible for the owner of a young plantation to form any reasonable estimate of its probable future production".

Anderson (1930) states:

> "the estimation of the probable timber production of a given area of ground is an essential matter whenever it is proposed to utilise such ground for planting, so that a reliable basis for arriving at such an estimate would be of great value".

A national survey carried out on these early plantations in the period 1917 to 1919 provided the first reliable information on the productivity of British conifers. Guillebaud and MacDonald (1928) were able to show clear relationships between productivity and elevation for Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Mill.) and Norway spruce (*Picea abies* (L.) Karst.). They classified the plots according to a subjective score of exposure and were able to show that tree growth rates were also related to exposure. The influence of soil type was less obvious as "elevation and exposure tended to obscure any influence due to the texture of the soil". Anderson (1930) used the same data to divide Scotland into " exposure zones" for which he gave values of average productivity levels likely to be achieved at specific elevations on good, average and poor soil types.

A programme of research into afforestation techniques was initiated soon after the formation of the Forestry Commission in 1919. Progress in the development of practices suitable for upland sites came about by a mixture of results from carefully controlled experiments and evidence from plantations established using the most promising techniques currently available.

The main advances were made in site amelioration techniques and species choice. After 1920 increasing use was made of exotic species. A system for matching species to site gradually evolved, site being described in terms of its vegetation and soil (Anderson 1950). Spruces were favoured on wetter sites and their higher growth rates compared with the pines and larches soon became apparent (Guillebaud and Macdonald 1928, Zehetmayr 1954). The potential of Sitka spruce in Britain particularly on exposed sites became obvious early in the century (Crozier 1910, Stirling-Maxwell 1931, Robinson 1931).

Site classification was aimed initially at simply achieving a "satisfactory" crop by means of correct species choice and cultivation method (Anderson 1950). According to Anderson the methods available for this were:

1. The use of information from stands in the area.
2. The use of data from measured sample plots in the vicinity.
   but since felled
3. The use of vegetation as a reflection of the influence of
   "major locality factors".

For the majority of foresters vegetation remained the key to assessing the productive capacity of sites. The first method was occasionally used, for example by Dier (1944) who studied the productive capacity of Deeside and investigated the relationships between site factors and productivity. He was able to show relationships between productivity and both elevation and a subjective assessment of "exposure".

Advances in site amelioration techniques and species choice achieved largely by the Forestry Commission research branch during the period 1920 - 1960 were associated with two major trends in upland afforestation:

1. A shift in emphasis away from matching species to site and towards altering a wide variety of sites to suit a restricted number of high-yielding species, particularly Sitka spruce.
2. The afforestation of increasingly high elevation and exposed sites.

By the 1960's site amelioration techniques had advanced sufficiently to allow the planting of Sitka spruce on a wide range of upland sites. Sitka spruce consistently outstripped other conifers in terms of yield, particularly on high elevation sites. Planting limits were pushed upwards in a piecemeal fashion as site amelioration techniques improved and better quality land be came increasingly scarce. The "commercial planting limit" became a special consideration in site productivity assessment on high elevation sites, for which little information was generally available.

1.1.2 Recent studies.

The earliest scientific study of the relationships between site and yield in Britain was carried out by Day (1946). He assessed factors such as elevation, aspect, slope, and soil type in Mynydd Ddu forest and related them to yield class using correlation and regression techniques. He was able to show relationships between productivity and both soil and topographic variables, including elevation and soil depth.

The influence of climatic factors on forest productivity was the subject of several studies starting in the 1950's (Anderson and Fairbairn 1955, MacDonald et al. 1957, Fairbairn 1960, Birse and Dry 1970, Malcolm 1970). Detailed descriptions of the gross climate were given but the possible effects on forest productivity were, with the exception of Malcolm (1970), not backed with data.

A series of studies of the relationships between site and productivity using advanced statistical analysis began in the 1960's, building to a large extent on methods developed in the USA (Kinloch and Page 1966, Page 1967, 1970, Adu 1968, Malcolm 1970, Cook 1971, Dixon 1971, Malcolm and Studholme 1972, Morgan 1972, Blyth 1974a, Cook et al. 1977, Mayhead and Broad 1978, White 1982a, 1982b). A list of the main site factors investigated together with an indication of significant correlations with productivity for those studies concerning Sitka spruce is given in Table 1.

According to Blyth (1974a) such studies generally have the dual aims of:

1. Elucidating the causal relationships between (ie. the processes linking) site factors and growth.
2. Classifying land or site according to its potential productivity.

Several of these studies involved the assessment of a great number of site factors and often more than one measure of productivity. This was because it was generally accepted that the relationships between site and growth were complex and involved many factors so that the inclusion of as many as possible would give:

1. Some idea of their relative importance.
2. A more comprehensive picture of the "factor complex".

Site factors ranged from the large scale and integrative (eg. elevation) to the small scale and specific (eg. extractable potassium in the organic layer). The general assumption was that large scale factors would "set the scene" and be of greatest use for land classification, whereas the more specific factors might be closer to the biological growth processes and therefore help to establish causal relationships. Problems were encountered with some of the integrative factors in that they were not clearly quantitative (eg. soil type) and with the specific factors in that they showed great spatial variation (Blyth 1974a). Some workers concentrated of identifying "land facets" which were homogeneous in certain key respects (eg. lithology, aspect) as a means of overcoming the problems posed by the spatial variability of certain site factors (physiographic approach - see Blyth 1974a, McGarry 1979).

Certain trends did emerge from the results. Blyth (1974a) was able to list the main groups of factors "in order of their limiting effects on growth" as climatic, physiographic then edaphic. Summarising site-productivity studies carried out in north-east Scotland he concluded that most work showed an elevational pattern of site factor variation. Clear relationships between productivity and elevation were demonstrated for various parts of the country (Adu 1968, Malcolm 1970, Malcolm and Studholme 1972, Mayhead and Broad 1978). The most important physiographic factors were those which modified the local climate such as geomorphic shelter (Dixon 1971, Blyth 1974a, Cook et

Table 1. Site factors assessed in previous studies of site/ productivity relationships.

SITE FACTORS	Day 1946	Page 1967	Malcolm 1970	Studholme 1972	Blyth 1974	Mayhead + Broad 1978
Elevation	-	x	x	x	x	(x)
Geomorphic Shelter				x	x	(x)
Topographic Class			x			
Position on Slope		-	x		x	
Slope	-	-	-	-	-	-
Aspect	-		x	x	-	x
Shape of Contours		x				x
Distance from Sea						(x)
Rainfall					x	
Temperature						
Air					x	
Soil					x	
Vegetation Type			-	-	-	
Soil Series		-				
Soil Type			-	-	-	
Soil Depth						
Total Rooting	x	x	x	-	-	
Organic Layer	x		x		x	
Effective Depth/Vol.			-		-	
Soil Moisture Cont.		x				
Soil Bulk Density		x			-	
Soil Texture		-		-	x	
Soil pH		-	-	-	-	
Soil Nitrogen						
Total			-		-	
Organic			-		x	
Mineral			x		-	
Soil Phosphorus						
Total			-		-	
Organic			x		-	
Mineral			-		x	
Soil Potassium						
Total			-		-	
Organic			-		x	
Mineral			-		-	
Soil Magnesium						
Organic			-		-	
Mineral			x		x	
Soil Calcium			-		-	
Soil Carbon			-			

x significantly correlated with productivity (GYC where applicable).
- assessed but not significantly correlated.
() symbols in parentheses indicate that the effects of these factors were significant when combined in regression equations, but not when considered singly.

al. 1977). Soil chemical effects were generally more important than soil physical (Malcolm 1970), particularly soil phosphorus and soil nitrogen levels.

In several cases there was a tendency for large scale and integrative factors to be closely correlated with productivity and these acted to obscure the effects of the more specific ones (Malcolm 1970). In addition many of the factors were intercorrelated so that a significant relationship between one site factor and growth could well be an expression of the effect of a second intercorrelated site variable. In some cases apparent correlations were due more to the nature of the sampling strategy or the distribution of plantations with respect to different site variables than to any causal relationship (Day 1946, Mayhead and Broad 1978). Although some success was achieved in land classification studies, these investigations often fell short of their second aim of elucidating causal relationships. One of the major achievements of these studies was demonstrating the complexity of the problems under scrutiny. A comprehensive critique of the methods adopted in many of these studies is given by McGarry (1979).

1.1.3 Methodology of site-productivity studies.

Rennie (1962), Ralston (1964), Carmean (1975) and Hägglund (1981) have reviewed research into assessment of forest site productivity. Two main approaches to the classification and description of forest sites are apparent. A site may be classified according to the performance of the tree crop on it, a method which has led to the development of yield models. Alternatively site classification may be based on attributes of the site which are known to be related to tree performance. Studies of the relationships between site factors and productivity inevitably draw heavily upon the methodologies of both approaches.

Relationships between site and productivity can be studied at various levels. At one extreme, site can be expressed in terms of its gross characteristics such as location or elevation and productivity in terms of rate of production of a volume of timber per hectare. At the other, physiological processes concerned with growth become the subject of investigation, with site being expressed as specific environmental variables and productivity as responses in assimilation or growth. At this level mathematical modelling has been applied with some success (eg. Running 1984), as well as the more usual correlation techniques. Both approaches are essential in gaining a full understanding of the relationships between site and productivity.

Innumerable studies have been carried out which have demonstrated the relationships between specific environmental variables and assimilation, growth and productivity . The role of some of the more important climatic factors have been reviewed by Kozlowski (1962), Grace (1977) and Tranquillini (1979). Tamm (1964) has reviewed the nutritional factors in relation to tree growth. Coile (1952, 1960), Della-Bianca and Olsen (1961) and Carmean (1973) have reviewed the role of soil attributes in the relationships between site factors and growth. Given present methods, many of these specific factors, both climatic and edaphic, are too difficult to assess in the field to be of direct use in predicting the productivity of forest land and for this reason they were not included in the present study.

An approach using major site factors, rather than more specific environmental variables, is most likely to yield means of assessing the productivity of forest land in the short or medium term, for applications which only require moderate precision and superficial knowledge of the processes involved. The current needs of the forest industry for yield prediction on exposed sites fall into this category.

Easily assessable major site factors which have shown the most consistent relationships with productivity in Britain are:

1. Those which affect the overall climates of sites, particularly elevation (Malcolm 1970, Mayhead 1973).
2. Those which modify the climate locally, particularly geomorphic shelter (eg. "topex", "relative elevation"), aspect and possibly slope (Blyth 1974a).
3. Soil factors, particularly soil type and rooting depth (Malcolm 1970, Blyth 1974a, Pyatt 1977).

The above factors are largely integrative, that is they integrate the effects of a large number of more specific processes. They are also fairly distant from the physiological growth processes which govern growth. For these reasons they are not particularly suitable for elucidating causal mechanisms in the relationships between site and tree productivity.

One possible way of moving slightly closer to the processes governing tree growth is to include extrapolated meteorological data in studies of the relationships between site and productivity. Extrapolated meteorological data have been used as an aid to site classification in a number of studies particularly in North America. On a regional scale climatic information has been used together with gross physiographic factors such as landform and lithology to classify land into units to which specific management practices, such as species choice, can be applied (eg. Booth 1985). Climatic indices have also been related to forest productivity on a regional scale (eg. Varjo 1972). Extrapolated meteorological data have been related to forest productivity on a forest stand scale (Hunter and Gibson 1984, Running 1984). In the present study it was felt that climatic effects might be better described by using extrapolated meteorological data rather than by simply relying on conventional site factors such as elevation. For this reason considerable effort was spent in investigating the relationships between extrapolated meteorological data and forest productivity.

1.1.4 Practical guidelines for the prediction of the productivity of conifers in Britain.

Quantitative guidelines for predicting the growth of conifers in Britain are few and are generally based more on subjective judgements than on data. MacKenzie (1959) gives a means of arriving at the production of unploughed, unfertilised stands using "scores" for rainfall, elevation, exposure, soil type and original vegetation. Pyatt (1977) gives estimates of productivity for specific site types in Wales, site being classified according to soil type. Toleman and Pyatt (1974) and Toleman (1975) classified the land area of Great Britain into "site regions" as an aid to forest management research. A site region was defined as "an area on a given lithology with relatively consistent soil type distribution, landform and climate". Busby (1974) gives "guides to yield class by soil group and elevation zone from empirical data and experience" but gives no details of how the estimates were arrived at.

In practice, estimation of the productivity of forest land is generally a matter for local experience.

1.2 Assessment of planting limits.

Assessment of planting limits is in many senses simply a specialised form of site productivity assessment in which a judgement has to be made about the most unfavourable site conditions under which a specific level of productivity can be achieved. In 1930 Anderson wrote: "the question of how far up on the slopes of hills and mountains it is possible to plant trees has frequently been discussed", showing that the problem has been appreciated for many years. The various ways available for assessing planting limits are detailed below.

1.2.1 The natural treeline.

One possible indicator of planting limits were the few remnants of natural treeline in Scotland which appeared to be unaffected by man. The altitude of the treeline in Scotland was the source of speculation as early as 1912 (Schröter), and has remained the subject of occasional research since (Watt and Jones 1946, Poore and MacVean 1957, Spence 1960, Pears 1967, 1968, Schofield 1980). Pears estimated its height in central Scotland as 610 m on windward slopes and 685 m on sheltered ones. Poore and MacVean quote values as low as 91 to 135 m in some west coast areas.

1.2.2 Plantation growth.

The wide use of exotic species and improved establishment techniques have effectively increased the elevation to which productive forests can be planted (Crozier 1910, MacDonald 1951).

Anderson (1930) used the 1919 census data to give the first and in fact only systematic attempt to describe planting limits in Scotland. He divided the whole country into "exposure zones" and gave predicted upper elevation limits for each quality class (yield class) on poor, average and good soil types. For average soil condition these ranged from 215 m in coastal areas to 610 m in central parts of Aberdeenshire. Dier (1944) gives proposed planting limits for the Dee valley above which a satisfactory mean annual increment of 40 ft^3 $acre^{-1}$ yr^{-1} (2.8 m^3 ha^{-1} yr^{-1}) would be unlikely to be achieved in the case of Scots pine. This limit was about 200 m above the valley floor, ranging from 260 m near the east coast to 550 m at Braemar, with an elevation as high as 780 m proposed for unplanted areas in the Cairngorm mountains. More recently

Mayhead (1973) studied the decrease in the growth of Sitka spruce with increasing elevation at various sites in Britain and noted a wide variation in the elevations at which a yield class of 6 was predicted in different areas.

1.2.3 Trial plots.

Beginning in 1922, the Forestry Commission established a substantial number of trial plots and plantations (pilot plots) on what were considered to be particularly exposed sites, with the aim of determining elevational limits to economic afforestation (Edwards and Wood 1957, Neustein 1965). These plots were established with what was currently the most promising species and establishment techniques and acted as local guidance as to the potential of various site types. Subsequent advances in afforestation practices often rendered these plots obsolete and many were later engulfed in new plantations, remaining of interest only as "museum pieces". One major problem with many of the earlier plots was their small size which rendered them susceptible to exposure damage to the edge trees (edge effects) such that genuine plantation conditions were rarely achieved.

Some of the better conceived trial plots have been of lasting value and have served as important indicators both locally and nationally of planting limits and the effects of severe climatic conditions on tree growth. An outstanding example was planted at Clatteringshaws forest in Galloway in 1955 where a series of four plots span a range of elevations from 503 m to 610 m. On the basis of the performance of these plots a planting limit at 560m was established in 1964 which has subsequently been shown to be correctly placed (Gale and Anderson 1984).

1.2.4 Tatter flags.

The primary means of assessing the height of the planting limit in areas where plots were not available was by means of tatter flags. Lines and Howell (1963) and later Saville (1974) were able to relate the rate of attrition of cotton flags ("tatter flags") to the growth rate of trees on exposed sites and so established tatter flags as a valuable simple tool for the assessment of site wind-climate. Studies of the tattering of flags in both controlled and field conditions have shown that the rate of tatter is well correlated with wind run, but is also influence by factors such as rainfall and atmospheric moisture (Rutter 1966, 1968a, 1968b, Jack and Saville 1973). Annual variation in windiness made it necessary for flags to be flown for two or preferably three years before even a moderately dependable estimate of site wind-climate was obtained (Lines and Howell 1963, Miller et al. 1987).

On the basis of early trials a tatter rate of 6.45 cm^2 day^{-1} was recommended as the limit for the successful establishment of Lodgepole pine and Sitka spruce (Lines and Howell 1963) but this was later revised to 13 cm^2 day^{-1} (Miller et al. 1987). Some variation was observed, with values as high as 14 cm^2 day^{-1} being acceptable in coastal areas of Scotland but only 12 cm^2 day^{-1} in central upland districts (Reynard and Low 1984). In the period 1954-1984 the Forestry Commission deployed over 1100 flags at over 100 sites in upland areas of Britain, some in experiments and others for the assessment of planting limits. It was soon observed that the different relationships existed between tatter rate and elevation in different parts of the country, and on the basis of these differences the concept of "windzones" was devised (Miller 1985).

1.2.5 Altitudinal limits for planting.

The combined evidence from trial plots, tatter flags and plantations led to a consensus of opinion that the economic limit lay at 500 to 550 m for the majority of northern Britain, but somewhat lower in coastal areas (Anderson and Edwards 1955, MacDonald et al. 1957, Malcolm and Studholme 1972, Mayhead 1973, Gale and Anderson 1984).

1.3 Exposure damage.

Many of the higher elevation or more exposed plots showed deformation of the crowns and branches and loss of needles, symptoms which became known as "exposure damage". The severity of this damage increased with increasing elevation and exposure. Symptoms were generally worse near the edges of plantations and plots, and were most obvious before crops closed canopy. The damage was thought to be due mainly to the effects of wind during the growing season, the specific mechanisms of which have recently been elucidated by Allen (1985). Some needle loss is also thought to occur during the winter due to abrasion and desiccation.

Early Forestry Commission experiments indicated that high levels of nutrition might alleviate exposure damage and promote growth on particularly exposed sites. This led during the 1970's and 1980's to the establishment of several experiments and plantations at particularly high elevations, which had very high nutritional inputs. First indications are that superior nutrition has only a minor effect on growth and the occurrence of exposure damage.

1.4 Objectives of this study.

The general objective of this study was to develop a basis for predicting the yield of Sitka spruce from easily assessable site factors in upland forests in northern Britain, for use in land acquisition and investment decisions, production forecasting and land use planning. It was felt that previous studies had demonstrated that potentially useful relationships existed between a relatively limited number of major site variables such as elevation and geomorphic shelter, and that such easily assessable factors might form a useful basis for a practical system of yield prediction, particularly for exposed sites. Extrapolated meteorological data were also included in the study to help to establish relationships between productivity and climatic factors.

In view of both the obviously overriding influence of elevation on the productivity of upland sites and the importance of upper planting limits it was decided that investigation of the role of elevation should be given great prominence. Accordingly, the following particular aims were identified:

1. To quantify the variation in yield class with change in elevation in different parts of Scotland and northern England, and to investigate possible geographical patterns in the productivity-elevation relationship.
2. To investigate the role of environmental factors in determining and modifying patterns noted in 1. above.
3. To identify easily assessable environmental factors which limit the growth of Sitka spruce on exposed sites.
4. To define upper planting limits in different parts of Scotland and northern England.

CHAPTER 2

METHODS

Introduction.

In this study "site" is regarded as the totality of environmental conditions which affect the development of the forest crop. The word "site" will also be used to describe the location of, for example, a tree crop, illustrating the ambiguous meaning of the word. Site "factors" or site "variables" are terms used to describe the properties of the location of the tree crop (ie. the site) which affect crop development. Malcolm (1970) and Kreutzer (1979) examine alternative concepts of site in some detail.

2.1 Factors assessed at each site.

The factors assessed at each site are shown in Table 2, together with the method of assessment where appropriate. The following sections give a brief description of the factors chosen and a justification of their inclusion in this study.

2.1.1 Productivity

The measure of productivity chosen in this study was yield class, which is an estimate of the maximum mean annual increment of stem volume per hectare per year. This is probably the best measure of the productive capacity of a site given our present state of knowledge (Kreutzer 1979).

Yield class is a long established and widely applied measure of the productivity of forest sites in Britain. In common with yield models in other countries, yield class is estimated from the height growth development of a sample of the dominant trees in the stand, in this case the 100 trees of greatest breast height diameter per hectare (Edwards and Christie 1981). Rather than expressing productivity in the form of a "site index" (ie. the mean height of the dominant trees at a predetermined age), height/volume functions are used to convert top height to maximum mean annual volume increment. As well as a standard height/volume function, alternative functions are available to help take account of local variations in growth patterns ("Local Yield Class" -

Table 2. Factors assessed at each plot and method of assessment.

FACTOR	METHOD OF ASSESSMENT
CROP	
General Yield Class (GYC)	from top height/age functions
Local Yield Class (LYC) u	from total basal area/top height functions
Basal area (BA) u	
Diameter (DBH)	girthing tape
Top height	heighting poles (young crops) climbing/tape (pole stage crops) optical hypsometer (mature crops)
Height to Diameter Ratio	
Age	FC stock map and records
TOPOGRAPHIC FACTORS	
Elevation	altimeter FC 1:10,000 forest stock map
Topex	prismatic compass and optical clinometer
Aspect	prismatic compass
Slope	optical clinometer
SOIL FACTORS	
Soil type	soil pit
Soil depth (where appropriate)	measuring tape
Rooting depth	measuring tape
CLIMATIC FACTORS	
Windzone	FC maps
Estimated tatter rate	FC tatter data (see chapter 4)
Estimated monthly mean summer temperatures	Meteorological Office records (see chapter 4)
Estimated mean accumulated temp. > 5.6°C	Birse and Dry 1970, Bendelow and Hartnup 1980 (see chapter 4)
Estimated rainfall	Meteorological Office maps
Estimated potential water deficit (class)	Birse and Dry 1970
Oceanicity (class)	Birse and Dry 1970
u for unthinned crops only.	

LYC).

Carmean (1975), Kreutzer (1979) and Hägglund (1981) have reviewed the methodology and problems involved in the construction of yield models. The main problems cited are:

1. The choice of sample plots may not accurately represent the forest area to which the model is to be applied.
2. Random or systematic errors may occur in the choice of dominant trees in the plots.
3. Difference may occur between the actual dominant height development and the pattern predicted by the height/age curves.
4. Considerable variation may occur in values of maximum mean annual increment for crops with similar patterns of height growth development. These differences may be site related.

The problems cited in 1. and 3. above are relevant in the case of crops growing at high elevations and on exposed sites. Inspection of Forestry Commission records used in the construction of the yield models shows a bias towards the siting of the permanent sample plots at low elevations and in areas of favourable growth. Figure 1 contrasts the elevational distribution of plots in this study with Forestry Commission sample plots. Height development patterns are to a certain extent site specific (Assman 1970, Beck and Troedsell 1973, Hägglund 1981) and there is reason to believe that the height development of trees at higher elevations could deviate from that displayed in low elevation crops due to the differing environmental factors dominating growth. Wind is a powerful factor in determining the growth patterns of tree stems (Larson 1965) and several authors have found changes in the height/diameter ratio of trees with increasing elevation (Malcolm and Studholme 1972, Blyth 1974a, Hughes 1979). In the case of Sitka spruce exposure to high winds causes the continual loss of leading shoots, which must have some consequences for the pattern of height growth development. Hughes (1979) estimated that 5 to 15 per cent of trees lost their leaders annually on an exposed site near Aberdeen, Scotland and in areas near the planting limit figures were as high as 30 per cent in certain years. It is possible that neither the standard height/volume function nor the local variants adequately express such effects.

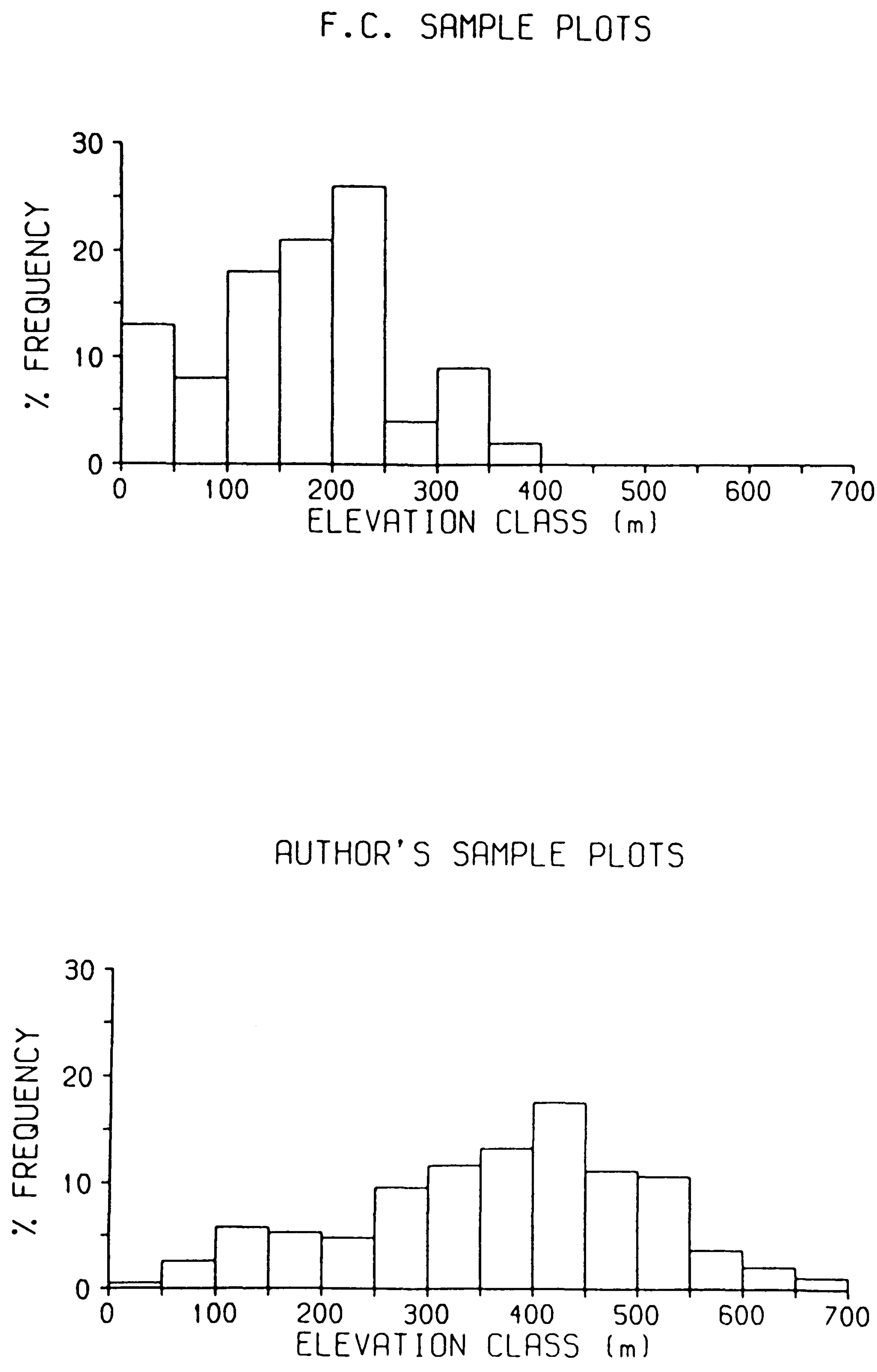


Figure 1. Frequency distribution of F.C. sample plots and plots in this study with respect to elevation

In addition, growth in the establishment phase can be altered by various factors and this can influence estimates of yield class throughout the entire life of the crop. The two main problems in this respect in upland Britain are:

1. The detrimental effects of "heather check" (competition with *Calluna vulgaris* L.) on the growth of Sitka spruce (Blyth 1974a, 1974b, Malcolm 1975).
2. The use of fertilisers which can give a boost in growth rate which may not be maintained later in the life of the crop (McIntosh 1981).

Such effects can have drastic effects on estimates of yield class, especially those made early in the life of the crops. In the present study efforts were made to avoid areas with special establishment problems or areas which had received non-standard fertiliser treatments. Heather dominated sites were included only where suitable silvicultural measures had apparently been taken to counter heather check.

Several investigations of the relationships between site and productivity, notably Blyth (1974a), have included alternative measures of productivity such as incremental height or diameter growth in addition to estimates of yield class. In this study General Yield Class (GYC) was chosen as the main measure of productivity because of its practical applicability and its uncomplicated assessment. The assessment of Local Yield Class (LYC) was also included, despite this requiring the time consuming estimation of basal area. LYC is intended to show up gross regional differences in growth and is not ideally suited for estimating the productivity of single plots, mainly because it is influenced by treatment to a greater extent than GYC. The main reason for including LYC was to investigate gross changes in tree form and therefore in productivity with increasing elevation and exposure. Other measures of productivity were excluded largely because of the limited time available at each plot. The height/diameter ratio of the top height trees was also calculated for each plot.

2.1.2 Physiographic factors.

2.1.2.1 Elevation.

Productivity decreases with increasing elevation due to the influence of increasingly adverse soil and climatic conditions. Some evidence for this effect in the case of British forestry has been given in chapter 1. A detailed account of the specific effects of elevation on the productivity of forests is presented in section 3.1. Elevation was measured in all cases with reference to mean sea-level.

2.1.2.2 Topex.

Topex is the sum of the angles of elevation from the observer to the horizon at the eight main compass points. The assumption behind topex is that the degree of shelter afforded by the surrounding topography is related to the angle of elevation to the skyline. The topex method provides the only simple quantitative measure of geomorphic shelter available and has become firmly established in British forestry (Miller et al. 1987). However it represents a gross simplification of a very complex phenomenon. The main problems with its use are:

1. It is unlikely that the degree of shelter is linearly related to the skyline angle as is implicit in the method. Non linear scales have had to be devised for the application of topex to problems such as windthrow hazard classification (Miller 1985).
2. Topex does not take account of the distance of the skyline from the observer. Thus a high distant mountain top is regarded as having the same effect as a smaller hill nearer to the observer.
3. These simplified relationships are assumed to prevail irrespective of windspeed or prevailing wind direction.
4. No account is taken of windflow patterns caused by the surrounding topography eg. wind-funnelling along valleys or over cols.

Despite these problems topex has been shown to be correlated with the growth of Sitka spruce (Blyth 1974a, Studholme 1968, Mayhead and Broad 1978), Douglas fir (Dixon 1971) and Scots pine (Adu 1968, Cook et al. 1977). Busby (1974) includes topex in his practical guide to the growth of conifers. Correlations have also been demonstrated between topex and flag tatter rates (Howell and Neustein 1965) and topex is included in the windthrow hazard classification system (Miller 1985). Topex has been shown to be more reliable in areas of relatively gentle topography rather than where the landscape is deeply dissected (Pyatt, D.G. pers. comm.).

As well as describing shelter from wind, topex is also correlated with soil conditions to the extent that sites receiving water and nutrients tend to occur in positions of high geomorphic shelter, whereas shedding sites are usually associated with low geomorphic shelter. Topex is also related to elevation, the nature of this relationship varying according to the gross topography of the area.

In this study topex was used in favour of other simpler methods of describing geomorphic shelter and topographic position such as "relative elevation".

2.1.2.3 Aspect.

Aspect affects the levels of solar radiation received at sites (Stage 1976, Baumgartner 1980, Roise and Betters 1981) and influences windflow patterns (Gloyne 1968, Nägeli 1971). Higher growth rates have been demonstrated on SW to NW facing slopes in Scandinavia (Skinnermoen 1969, Poso and Kujula 1973), on NE to SE facing slopes in Britain (Mayhead and Broad 1978, Cook et al. 1977) and America (Tajchman and Wiant 1983), on south facing slopes in the European Alps (Ott 1978) and on various aspects in America (Stage 1976, Roise and Betters 1981).

Aspect is usually included in studies of the relationships between site factors and productivity though significant effects of aspect on productivity or treelines are by no means universally found. One problem in many studies is that stands, or certain key attributes of stands, related to productivity are seldom equitably distributed with respect to aspect.

Aspect was included in this study because of its possible role in influencing the temperature and windiness of exposed sites. Aspect was recorded in degrees and treated as both a stratifying factor and a quantitative variable (transformed by sine/cosine functions).

2.1.2.4 Slope.

Angle of slope interacts with aspect to influence solar radiation levels and the degree of shelter afforded to trees (Stage 1976). Slope also has a certain bearing on soil water and nutrient movement particularly as slope angles approach zero. Slope was included in this study to give a complete picture of the physiography of sites in terms of major site variables. Correlations between productivity and angle of slope have been noted by Day (1946) and Mayhead and Broad (1978) though the majority of other studies have failed to reveal significant relationships.

2.1.3 Soil factors.

2.1.3.1 Soil type.

The classification of soils into different soil types gives a reflection of the properties of the soil parent material and the water status and climate of the site and as such represents a form of site classification (Pyatt 1970). Soil parent material largely determines the drainage properties and nutrient status of soils. The water status of soils is determined by the topography and climate of sites and is an important influence on nutrient cycling and rooting capacity. The climate of a site in terms of its wetness and warmth controls the rate of many soil processes including the breakdown of organic matter, root growth and water absorption (Pyatt 1970).

The main soil sequences (catenas) occurring in the British uplands are shown in Figure 2. Soil type has been used in site classification for practical purposes (Pyatt 1977, Busby 1974) and in detailed studies of the relationships between site factors and productivity in Britain (Malcolm 1970, Page 1967) and abroad (Carmean 1973). In areas of even topography soil factors assume relatively greater importance than climatic factors in studies of forest productivity. This partly explains the greater emphasis on soil properties apparent in American investigations (Myers and Van Deusen 1960). In the British uplands both soil and climatic factors are important, with climatic factors apparently dominating (Blyth 1974a). The picture is complicated by the fact that climate is a major influence on soil development as well as on tree

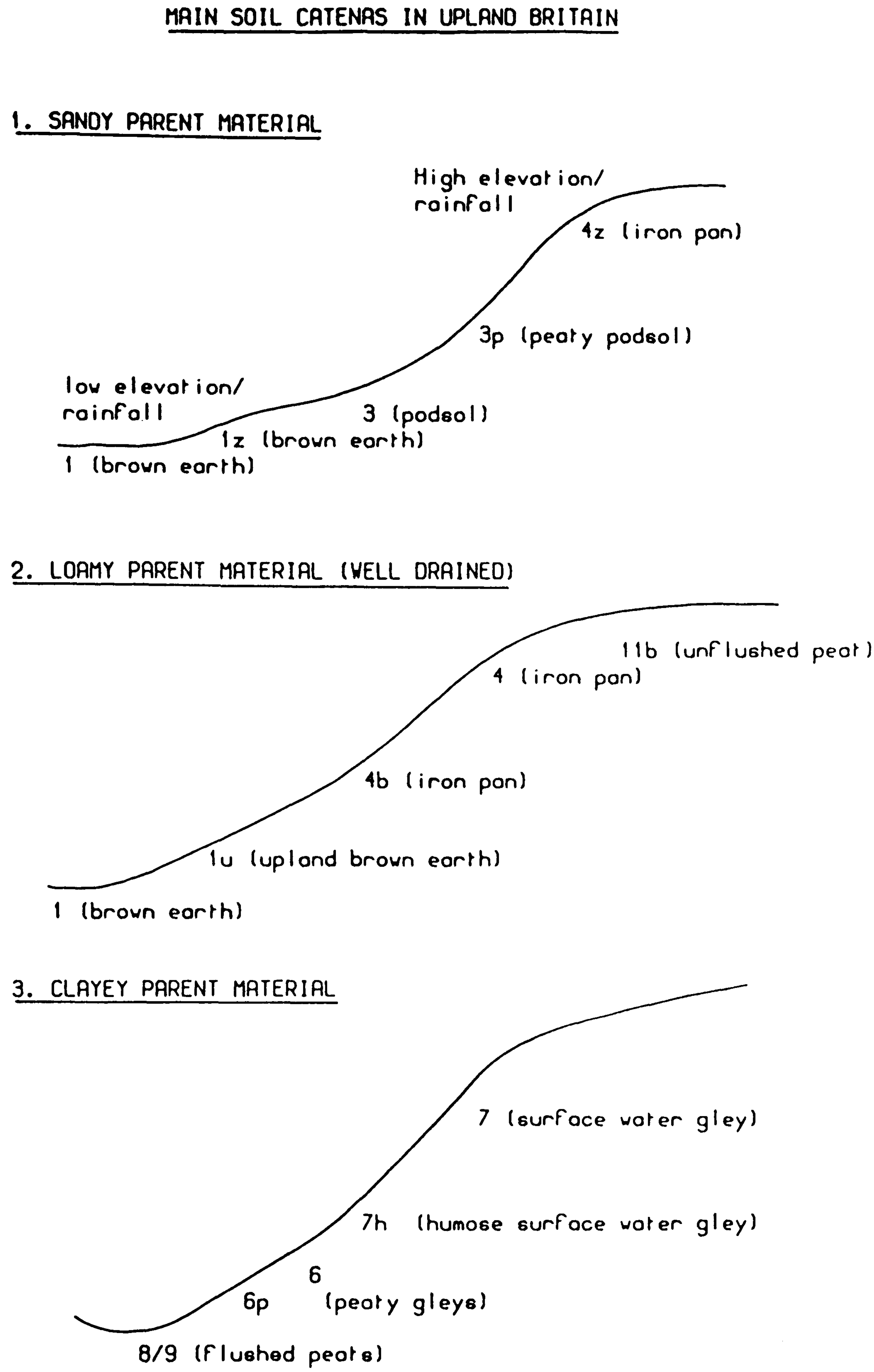


Figure 2. Main soil catenas in the British uplands

growth. Also, modern site amelioration practices such as ploughing, draining and fertilising are routinely carried out to remove limitations on productivity and these alter the original attributes of the different soil types.

Soil type was included in this study as the best easily assessable estimate of soil conditions.

2.1.3.2 Total soil depth and rooting depth.

Total soil depth and rooting depth give estimates of the soil volume available to tree roots for water, nutrient and oxygen supply. Rooting depth may be determined by physical impediments or by the level of the water table. Soil depth and rooting depth have been shown to related to productivity in Britain (Day 1946) and abroad (Myers and Van Deusen 1960), though such correlations were lacking in a number of major studies in Britain (Blyth 1974a, Page 1970).

Soil and rooting depth were included in this study to investigate possible effects of restricted rooting on productivity on upland sites.

2.1.4 Climatic factors.

2.1.4.1 Temperature.

Estimates of mean accumulated temperature above 5.6 °C and the mean temperatures of the four warmest months (July - September) were made by extrapolating values from standard meteorological stations using standard lapse rates. Details of the derivation of these estimates and an account of the effects of temperature on tree growth are given in Chapter 4.

2.1.4.2 Wind.

Estimates of the wind-climate ("windiness") of sites were made from Forestry Commission tatter flag data, details of which are given in section 4.2.4. A detailed account of the effects of wind on tree growth is given in section 4.1.2.

2.1.4.3 Rainfall, potential water deficit, oceanicity.

Sitka spruce is a maritime species, thriving best in the conditions of relatively high humidity and rainfall (Schober 1962), which characterise many upland sites in Britain. In Britain considerable differences exist between west coast sites and drier areas in the Eastern Highlands (Birse and Dry 1970), and these have been linked to the productivity of Sitka spruce (MacDonald et al. 1957, Blyth 1974a). In this study rainfall was estimated from meteorological maps (Meteorological Office 1977), and potential water deficit in four classes (25-50 mm and 0-25 mm deficit, 0-500 mm and 500 + mm excess) and oceanicity in three classes (hyper-, eu-, and hemioceanic) from climatic classifications of Scotland by Birse and Dry (1970) and of England by Bendelow and Hartnup (1980).

2.2 General experimental procedure.

Data were collected by establishing 187 0.04 ha temporary sample plots located at 37 sites distributed over Scotland and northern England. Productivity (yield class) and site characteristics were assessed on a single visit basis, further data being provided subsequently by reference to maps and meteorological records. One of the major aims of the project was to investigate the effect of elevation on productivity. For this reason plots at the majority of sites were established in series at regular height intervals. To increase the geographical spread of the data, single plots or small groups of plots were also established in certain areas, particularly where difficulty was encountered in locating suitable areas of plantation for full scale sites. These supplementary plots were located, where possible, at Forestry Commission high elevation experiment sites or at sites where tatter flags had previously been flown.

The overall aims of the analysis were:

1. To study the decline in productivity with increasing elevation at the different experimental sites.
2. To investigate the influence of other site factors, particularly climatic ones, on productivity.
3. To pool the data, investigate regional patterns in the trends noted in 1. and 2. above and attempt to identify potentially useful global models.
4. If necessary, to stratify the data by region and produce regional

models.

Analysis was intended to rely largely on correlation and regression techniques, but other multivariate techniques were to be included if they proved useful.

In investigations of this type, a balance has to be struck between on the one hand collecting a large amount of data from a relatively small number of plots or on the other, collecting a lesser amount of data from a large number of plots. In this study the balance was strongly in favour of the latter approach, partly because it was intended to cover a wide geographical range. In addition many of the sites were difficult of access, and many of the crops difficult to operate in. This meant that a comparatively large amount of time was required for travelling and laying out of the plots, thus restricting the time available at each plot.

The criteria for the choice of sites and the distribution of sites and plots are detailed below.

2.3 Distribution of experimental sites.

Sites were distributed as far as was possible over the whole of Scotland and northern England (see Figure 3). In view of the important effect of "exposure" on growth rates in the uplands, special efforts were made to ensure that western and northern coastal areas were represented, as well as the extensive areas of high elevation forestry in inland districts. This was done by stratifying the area by Forestry Commission windzones (see Miller 1985) and attempting to locate suitable sites in each of the five windzones. Difficulty was experienced in locating suitable sites in windzones A-C, proving totally impossible in windzone A (the Outer Isles and extreme west coast). This was generally due to the lack of crops of a suitable age. It was also difficult to find sufficiently large areas of continuous Sitka spruce in eastern Scotland. Both these areas are represented by single plots rather than by sites with series of plots.

Possible sites were located in the first instance by local Forestry Commission research head foresters, the final choice of sites being made by the author after visits to all of the proposed sites. The number of suitable sites proved to be surprisingly restricted and intentions of trying to ensure an equitable distribution of sites with respect to site factors such as soil type or

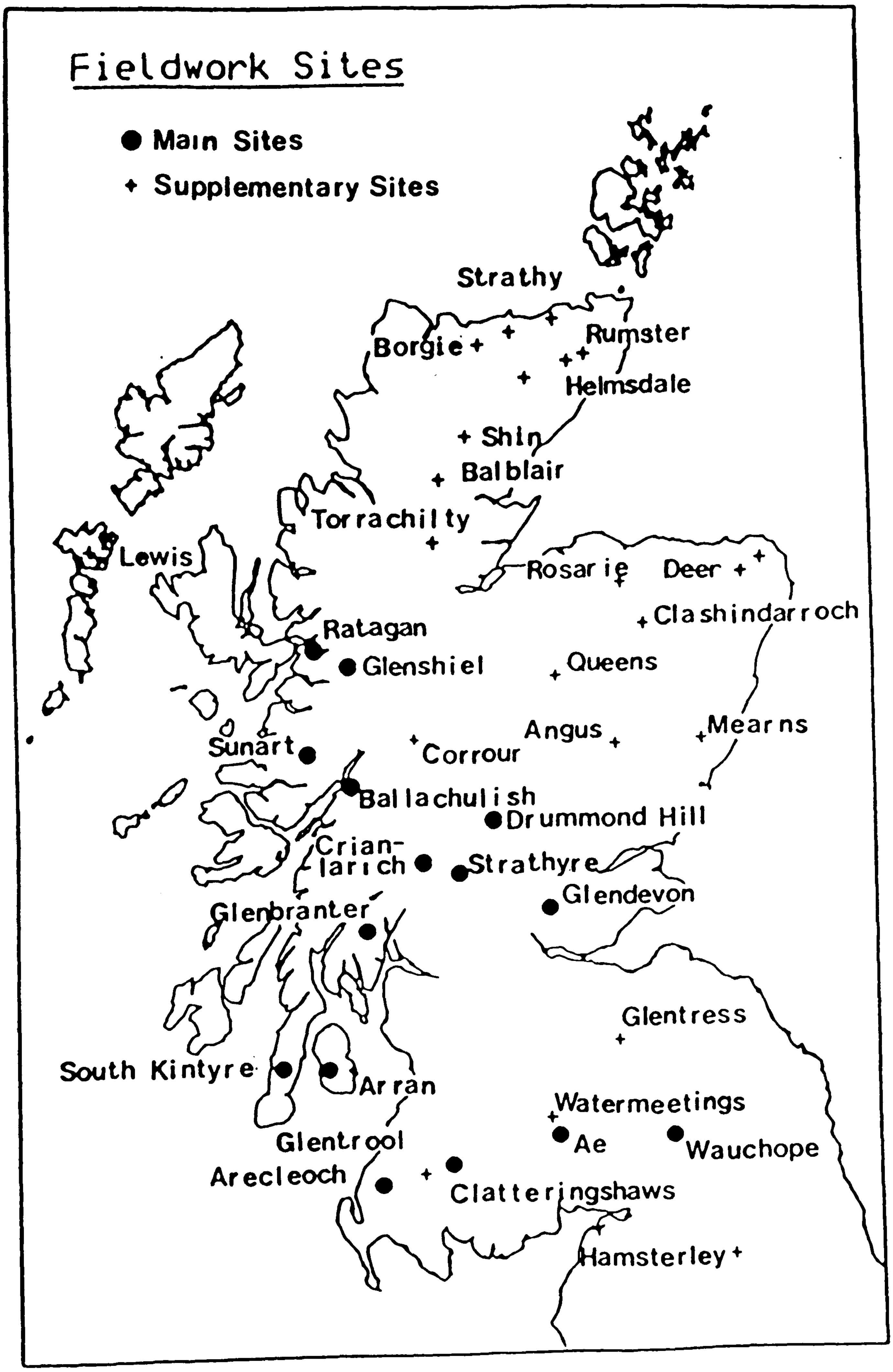


Figure 3. Location of fieldwork sites

aspect had to be abandoned.

Figure 3 shows the location of the sites and Table 3 gives an overview of the main site characteristics.

2.4 Choice of experimental sites.

The following constraints were applied to the choice of experimental sites:

1. Crops should consist of pure Sitka spruce extending more or less continuously over as large an altitudinal range as possible and terminating at or near the level considered locally as the upper planting limit.
2. The age of the crops should, where possible, be 15 years or older, with an age range of 20-30 years being preferred. This was to try to ensure that the crops were old enough to give reliable estimates of yield class but young enough to have received standard modern silvicultural treatment. Sites with a relatively even age structure were to be preferred to sites with widely differing crop ages.
3. The topography and the soil conditions of the slopes should not be unduly variable.
4. The sites and the performance of the crops on them should preferably be broadly representative of the surrounding area.
5. Crops should be free from extraordinary establishment problems such as poor drainage, frost damage, or heather check. Crops with obvious nutrient deficiencies were avoided.
6. Crops should be of Queen Charlotte Island provenance or similar.

The main factor which prevented the use of many potential areas was that high elevation plantations were generally too young. Crops under 15 years of age were included on one main site (Arran) and on 5 plots on Forestry Commission high elevation experimental sites. Crops older than 30 years were included on several sites where it was considered that the establishment

Table 3. Main site characteristics of experimental sites.

SITE NAME	No. of Plots	GYC range	Wind zone	Elevation	Topex range	Aspect	Soil type	Crop age
Major Sites								
Arecleoch	8	14-20	C	245-365	14-25	E	6,9	18-19
Clatteringshaws	10	6-16	D	393-580	56-71	WSW	6,7	20-21
Ae	5	10-16	D	470-540	34-42	ESE	6,7,9	28
Wauchope	10	10-20	D/E	308-427	8-33	WSW	3,6,7,9	23
South Kintyre	10	8-20	B	158-335	17-68	W	6,9,11	22
Arran	5	10-18	C	200-400	20-24	WSW	6,9	13
Glenbranter	10	8-16	D	248-440	64-90	NW	3,4,6,7	22,25
Ochil	10	10-24	E	350-598	19-88	NNW	4,6,7,9	14-18
Strathyre 1	10	12-18	E	338-562	80-112	E	1,4,6,7	50
Strathyre 2	4	8-14	E	425-500	81-92	WSW	3,4	49
Strathyre 3	5	8-20	E	460-540	47-90	W	3,6,7	25
Drummond Hill	10	12-20	E	355-540	57-69	SE	1,7	21,39
Crianlarich	11	14-22	E	231-450	45-61	N	6,9	18-19
Ballachulish 1	5	9-14	D	325-420	113-120	E	1,6,7	55
Ballachulish 2	5	6-14	D	340-440	113-129	W	1,6,7,13	53
Sunart	5	12-16	C	105-325	121-130	SW	6,7,9	50
Glenshiel	5	8-12	D	435-520	100-106	SW	4,6,7,9	52
Ratagan	5	22-26	B	40-260	76-82	NE	1,7	26

Table 3. (cont)

SITE NAME	No. of Plots	GYC range	Wind zone	Elevation	Topex range	Aspect	Soil type	Crop age
Supplementary Sites (e = FC experiments, t = FC tatter flag sites)								
Glentrool (t)	8	8-22	C/D	198-451	15-43	v	3,6,7,9	21-33
Watermeetings (e)	1	10	D	465	15	E	6	26
Glentress	2	6-8	E	567-586	33-34	WSW	4,6	21
Corrour (e)	1	16	E	365	20	SSW	9	14
Angus (t)	3	12-14	E	364-525	58-90	v	3,6	21-24
Queens (e,t)	2	6-8	E	632	63	WNW	4	15
Mearns (t)	2	16	E	350	13	N,NE	3,6	16,17
Clashindarroch (t)	7	10-18	E	408-473	4-34	v	4,6	24-26
Deer (e,t)	2	16	B/C	130-140	6-10	v	6,9	17,20
Rosarie (e)	1	16	E	320	9	NW	4	15
Torrachilty (e,t)	2	6-12	D/E	413-600	41-57	NE	9,11	15,16
Balblair (e,t)	2	14	D	305	16	NNE	9	15
Shin (e)	1	18	D	122	3	nil	9	10
Helmsdale (e,t)	2	10-16	C	170-294	15-21	v	4,9	15
Rumster (e)	3	14-16	B/C	90-121	1-29	v	11	10-35
Borgie (t)	6	14-22	B	100-170	7-30	v	6,9	16-35
Strathy (e)	1	16	B	106	13	E	9	15
Lewis (e,t)	3	12-16	A	53-114	24-28	v	11	10

v = various aspects.

techniques had not differed too greatly from modern practice.

2.5 Location of Plots.

2.5.1. Main sites (transects)

Eighteen main sites ("transects") were established where plots were located at regular intervals of elevation up the slope. The height intervals varied from site to site according to the vertical elevation range of the site. A total of 8-10 plots at 20 metre vertical height intervals spanning the upper 200 m of plantation was regarded as ideal but conditions where this was possible were only encountered on 9 sites. On nine other sites it was possible to establish 5-8 plots at 20-40 m intervals.

Transects were generally located parallel to rides running up the slopes. The plots were located far enough from the edges of crops to be unaffected by "edge effects" (ie. wind damage on exposed plantation edges) but close enough to ridesides to allow relatively easy access into what were often extremely inhospitable thicket stage plantations. This generally meant that plot centres were located between 20 and 60 metres from the edges of rides running up the slopes. The uppermost or lowest plot of the transect was located randomly within the constraints mentioned above, then the remainder of the plots were located at predetermined height intervals at random distances (between 20 and 60 metres) from the rideside.

In the case of plot centres falling in areas of obviously unhealthy or damaged trees, or where stocking was markedly lower than in the surrounding crops, plot centres were moved along the contour into the first apparently representative area of plantation. Due to the method of site selection employed, this procedure was only necessary in three cases.

2.5.2. Supplementary sites.

Nineteen supplementary sites were established to increase the geographical range of the data. As previously mentioned, these were located either:

1. In Forestry Commission high elevation experiments or other experiments on relatively exposed sites.
2. In the vicinity of sites where tatter flags had been flown prior to

planting.

3. In standard plantations in relatively exposed areas where areas suitable for major sites were not available.

In the case of categories 1. and 2. many of the relevant site variables had been assessed prior to planting and a certain amount of useful background information was available. At F.C. experimental sites, plots were located in, or previously assessed data were taken from, areas with treatments most akin to modern silvicultural practice. In the case of old tatter flag sites, plots were centred on the old flag posts which were located, often with a certain amount of difficulty, from six-figure grid references. In the case of standard plantations (Borgie, Helmsdale, Clashindarroch, Glentress), plots were located subjectively to give a representative picture of the local site.

2.6 Sample plot procedure.

1. The centre of the plot was located according to the procedure described in section 2.5 and was marked with a cane.

2. In thicket stage crops alternate row brashing was carried out on an area of approximately 0.02 ha around the plot centre to allow easier access within the crop.

3. The plot boundaries were established using measuring tapes and canes. In the case of regularly spaced crops, square plots were found to be most appropriate whereas in irregular crops circular plots were used. In the case of square plots, a 20 m by 20 m (0.04 ha) area was marked out in alignment with the direction of ploughing and within this a 14.1 by 14.1 m (0.02 ha) area was laid out. In the case of circular plots diameters of 22.6 m and 16.0 m were used for the 0.04 ha and 0.02 ha plots respectively, with their circumferences being marked at eight points. Suitable stepping procedures were used on slopes.

4. General Yield Class was assessed according to standard procedure (Edwards and Christie 1981) based on four trees on the 0.04 ha plot. Trees with broken leaders were so frequent in some areas that they had to be accepted as top height trees unless repeated damage had resulted in them being markedly lower than other dominants on the plot. The breast height diameters of all the

trees within the 0.02 ha plot were recorded to give estimates of basal area per hectare. This information was used to make estimates Local Yield Class.

5. Topex was assessed usually from the top of a dominant tree but occasionally from a nearby point on the ride. When misty conditions prevailed topex was calculated from 1:10,000 and 1:50,000 maps in a fashion similar to that described by Wilson (1984).

6. Slope was assessed from the plot centre as the average of upslope and downslope angles.

7. Aspect was assessed from the plot centre.

8. A soil pit was dug to a maximum depth of 1 metre midway between the two trees nearest the plot centre. The soil was classified according to the Forestry Commission system (Pyatt 1982). Rooting depth was measured to the deepest live root. Total depth was measured to compacted or rocky layers in the C horizon which were thought to seriously impede rooting (and digging !). Measurements were taken from what was estimated to be the original ground surface.

9. In the first field season increment cores were taken from the top height trees and the number of years taken to reach breast height was estimated. This gave an indication of the existence of early growth check. No instances of check serious enough to warrant adjustment of yield class values were encountered and this procedure was dropped during the second field season.

2.7 Reliability of measurements.

Some difficulty was encountered making measurements in some of the younger, denser crops. Top height measurements in crops of top height 14 m or less were made using heighting poles and were probably accurate to the nearest 0.2 m. In taller crops the preferred method of height measurement was using a hypsometer (precision approximately ±0.25 m). Where visibility was particularly poor, trees were measured by climbing, which probably maintained a level of precision of about ±0.25 m. Topex was generally measured from the top of a dominant tree and despite operational difficulties, this was often the only feasible way of making reasonably precise measurements. Topex measurements made from Ordnance Survey maps, which were resorted to in misty weather, are generally precise only to the nearest 5 - 10 ° (Reynard, B.R. pers. comm.). Considerable difficult was encountered in making measurements of angle of slope within dense crops, and these are probably reliable to within ±2 °. Some of the factors which influence the reliability of climatic data obtained from climatic maps and by extrapolating meteorological data are described in chapter 4.

CHAPTER 3

THE EFFECTS OF ELEVATION ON PRODUCTIVITY.

3.1 Introduction.

Changes in elevation affect many aspects of forest ecosystems and manifest themselves in many different ways including changes in species composition (natural forests), growth rates, productivity, form and reproductive capacity. A special feature of these changes is the treeline (timberline) above which high forest growth is impossible due to adverse environmental conditions.

Diminishing rates of productivity due to increasing elevation have been demonstrated for natural forests (eg. Kira and Shidei 1967, Grubb 1977, Maruyama 1971), semi-natural managed forests (eg. Tranquillini 1979, Benecke and Davis 1980) and forest plantations (eg. Malcolm 1970, Studholme 1968, Mayhead 1973). Similar effects have been shown for forest experiments using potted plants (eg. Benecke 1972, Tranquillini et al. 1978), for pasturelands (eg. Jones 1970, Hunter and Grant 1971) and for natural vegetation other than forest (Pearsall 1950).

In the case of natural forests, research has been largely ecologically orientated, demonstrating different levels of productivity and accompanying changes in species composition and growth form at varying altitudes (eg. Kira and Shidei 1967). In semi-natural forests in the European Alps, New Zealand and North America, research has been aimed at establishing the links between environmental factors, growth processes and production (Tranquillini 1979, Benecke and Davis 1980, Running 1984). In such forests the treeline is an important feature and has attracted a large amount of research. In plantation forestry decreases in productivity due to increasing elevation have been studied largely with a view to land capability assessment (Malcolm 1970, Mayhead 1973).

Declining productivity with increasing elevation can be expressed in various ways, including changes in total dry matter production, mean volume, height or diameter of the crop and increments in volume, height or diameter.

Information on changes in total dry matter production is scarce (Tranquillini 1979). Total above ground biomass decreased from 40 t ha^{-1} yr^{-1} to 20 t ha^{-1} yr^{-1} between 550 m and 1550 m in *Fagus crenata* in Japan (Maruyama 1971) and from 7 t ha^{-1} yr^{-1} to 5 t ha^{-1} yr^{-1} between 900 m and 1340 m in *Nothofagus solandri* in New Zealand (Wardle 1970). Kira and Shidei (1967) give a comprehensive picture of declining biomass production with increasing elevation in different climatic zones in the western Pacific region.

Decreases in total standing volume of about 3 m^3 per 100 m increase in elevation have been shown in Finland (Poso and Kujula 1973, Roiko-Jokela 1980). Decreases in timber volume increment have been demonstrated in several parts of the world and these are illustrated in Figure 4. The effect of latitude in determining the levels of productivity with respect to elevation is apparent. The altitude of the natural treeline is also affected by latitude, rising from near sea-level at 70 N. to about 700 m in southern Scandinavia, 2000 m in the European Alps, 3000m in Mediterranean areas and to over 4000 m in parts of the tropics (Baumgartner 1980).

Both linear and non-linear relationships between productivity and elevation have been recorded. In the majority of the British studies relationships between productivity and elevation were found to be linear (Malcolm 1970, Studholme 1968, Mayhead 1973). However Oswald (1969) showed relationships between tree height and elevation which were best described as third order polynomials for Norway spruce in France. Däniker (1923) and Ott (1978) recorded only slight declines in tree height up to about 1800 m in Switzerland but above this level tree height declined very rapidly (3-5 m per 100 m increase in altitude). Studholme (1968) found rather higher rates of decrease in productivity with increasing elevation amongst the highest plantations of Sitka spruce and European larch in Britain than did Malcolm (1970) sampling over the entire elevation range. Productivity at lower elevations can be limited by the moisture requirements of trees and this can lead to an optimum elevation for productivity occurring at moderate altitudes (Tranquillini et al. 1978).

Incremental height data have been gathered for both forest trees (Wardle 1970) and potted tree seedlings (Benecke 1972, Freezaillah 1974, Tranquillini et al. 1978). Holzer (1973 - quoted in Tranquillini 1979) showed that annual height increments of Norway spruce diminished from 30 cm at 700 m to 15 cm at the spruce treeline at 1700 m to under 10 cm on isolated spruce trees in pine/larch

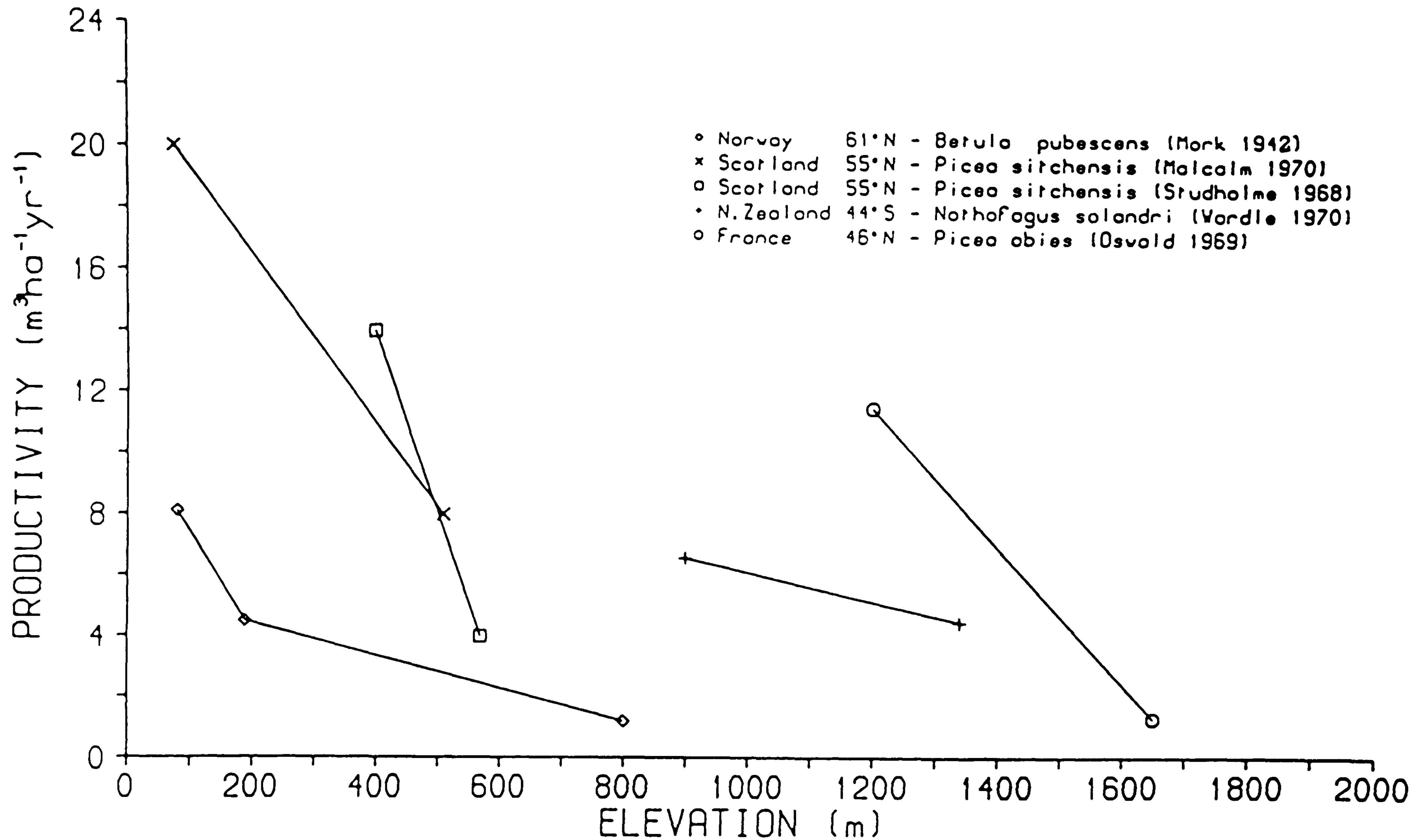


Figure 4. Productivity/elevation relationships in various parts of the world

forest at 1800 - 1900 m. In *Nothofagus solandri* in New Zealand mean shoot extension diminished from 40.5 cm to 4.9 cm between 820 m and 1350 m (Wardle 1970).

The use of potted seedlings growing at specific elevations allows comparison of growth patterns under controlled site conditions using plants of known origin. Tranquillini (1979) reviewed such experiments carried out in the European Alps and New Zealand. The height growth patterns of trees in natural populations were partly genetically based, with plants from higher altitude origins generally showing shorter growth periods and slower growth rates than plants from low elevation origins grown on the same sites. Budbreak was generally delayed at higher elevations by values of up to six weeks. Similar effects of elevation on the date of budbreak have been shown for Sitka spruce in Britain by Cannell (1985). Growth cessation was independent of elevation in some species (eg. larches) but was delayed by a similar amount as budbreak in species such as Norway spruce (Tranquillini 1979).

Freezaillah (1974) studied the effects of environmental factors and fertilising on potted seedlings of Sitka spruce growing at a range of elevations in Scotland and concluded that growth rates were primarily determined by the growing season temperature.

3.1.1 Factors causing reduced growth with increasing elevation.

The majority of environmental factors which influence tree growth vary with changes in elevation. This means that the influence of elevation on productivity is a complicated one and attributing effects to specific factors is problematic given the present state of our knowledge. Even distinguishing between climatic and edaphic factors can be difficult.

However, some trends are apparent. Probably the most important environmental factor causing growth rates to vary with changes in elevation is air temperature through its effect on plant tissue temperature and thus on photosynthesis and respiration (Tranquillini 1979). Temperature also controls the rates of cell division and shoot extension. A detailed account of the effect of temperature on tree growth is given in section 4.1.1.

Growing season length is an important factor which determines the time available to trees for the completion of growth, the maturation of tissues and the setting of buds. Growing season length diminished more rapidly in oceanic areas than continental areas due to the slower rate of change of temperature with time at the beginning and end of the growing season which occurs in oceanic climates (Manley 1945, Gloyne 1958, Taylor 1965).

Average windspeeds generally increase with increasing elevation (Grace 1977). Wind is a potent factor which affects growth by reducing plant tissue temperature, affecting plant water status, influencing stomatal opening and thus photosynthesis and also by mechanical shaking and damage (Grace 1977, Rees and Grace 1980a,b). A detailed account of the effects of wind on tree growth is given in section 4.1.2.

Adiabatic processes operating over mountain massifs affect cloud formation, humidity and the incidence of precipitation. Increased cloudiness leads to reduced light intensities and this may reduce photosynthesis. Increased humidity and rainfall levels are beneficial to productivity in many areas of the world though on upland sites in maritime areas such as Britain where significant water deficits are relatively infrequent, this is probably seldom the case.

In particularly high elevation areas of the world factors such as decreased atmospheric pressure, reduced partial pressure of carbon dioxide, increased solar energy flux, and ultra-violet enrichment of the solar spectrum may contribute to reduced growth (Daubenmire 1954, Wardle 1965, Tranquillini 1964, 1979, Benecke and Davis 1980). The frequency of some damaging events such as frost damage and snowbreak also tends to increase with increasing elevation (Cannell 1985, Worrell 1979).

Changes in soil conditions which may be linked with reduced productivity with increased elevation include soil temperature, nutrient availability, and water status. Soils also tend to become less mature, less stable and often shallower with increasing elevation (Pearsall 1950). These effects are reflected in changes in soil-type with elevation (catenas). Soil temperatures are linked to air temperatures (Russell 1973, Bocock et al. 1977), though the relationship is affected by a number of factors including the thermal conductance of the soil. Soil temperatures have been shown to decline with increasing elevation at similar rates to mean air temperatures in certain cases (Shanks 1956). Soil temperatures affect the rates of microbial and chemical activity in the soil and root growth rates and therefore influence nutrient availability. Although nutrient availability is a major factor influencing forest productivity, changes in nutrient levels are apparently of relatively minor importance in relation to changes in forest growth rates with increasing elevation, particularly near the treeline (Millard 1974, Nordmeyer 1980). Water relations during the winter period appear to be of considerable importance to tree growth near alpine treelines (Tranquillini 1979, Turner and Tranquillini 1985). Low soil temperatures inhibit water uptake and restrict water conductance within the plant. This in combination with with incomplete leaf cuticle development resulting from the short growing season, may lead to damaging levels of water stress (Tranquillini 1979).

In general climatic factors appear to exert a dominating influence on forest productivity at high elevations (Tranquillini 1979, Benecke and Davis 1980). However, making more specific statements about the relative importance of different environmental variables is difficult for several reasons. Firstly, many of the environmental factors affecting site-growth relationships are interrelated, for example air temperature with soil temperature and soil temperature with soil nutrient cycling. Many of the specific environmental variables (eg. air and soil temperatures) are also affected by gross topographic factors such as geomorphic shelter, slope and aspect, which are difficult to quantify. Further, many of the physiological processes governing growth are interrelated, for example transpiration and photosynthesis through the control of stomatal opening. Many of the plant responses to environmental factors are also to a certain extent genetically controlled, being specific to certain species or origins.

3.2 The effect of elevation on General Yield Class.

3.2.1 Individual sites.

The relationships between GYC and elevation were estimated by regression analysis for the 18 main sites. These are shown in Figures 5 a-i, together with the corresponding values for topex and angle of slope. The regression lines for all the sites are shown together in Figure 6. General Yield Class and elevation were closely related on the majority of sites, with elevation accounting for between 53 per cent and 98 per cent of the variation in GYC. The values of r^2 are higher than those reported in previous studies (Malcolm 1970, Studholme 1968, Mayhead 1973). This is probably largely due to the prior selection of

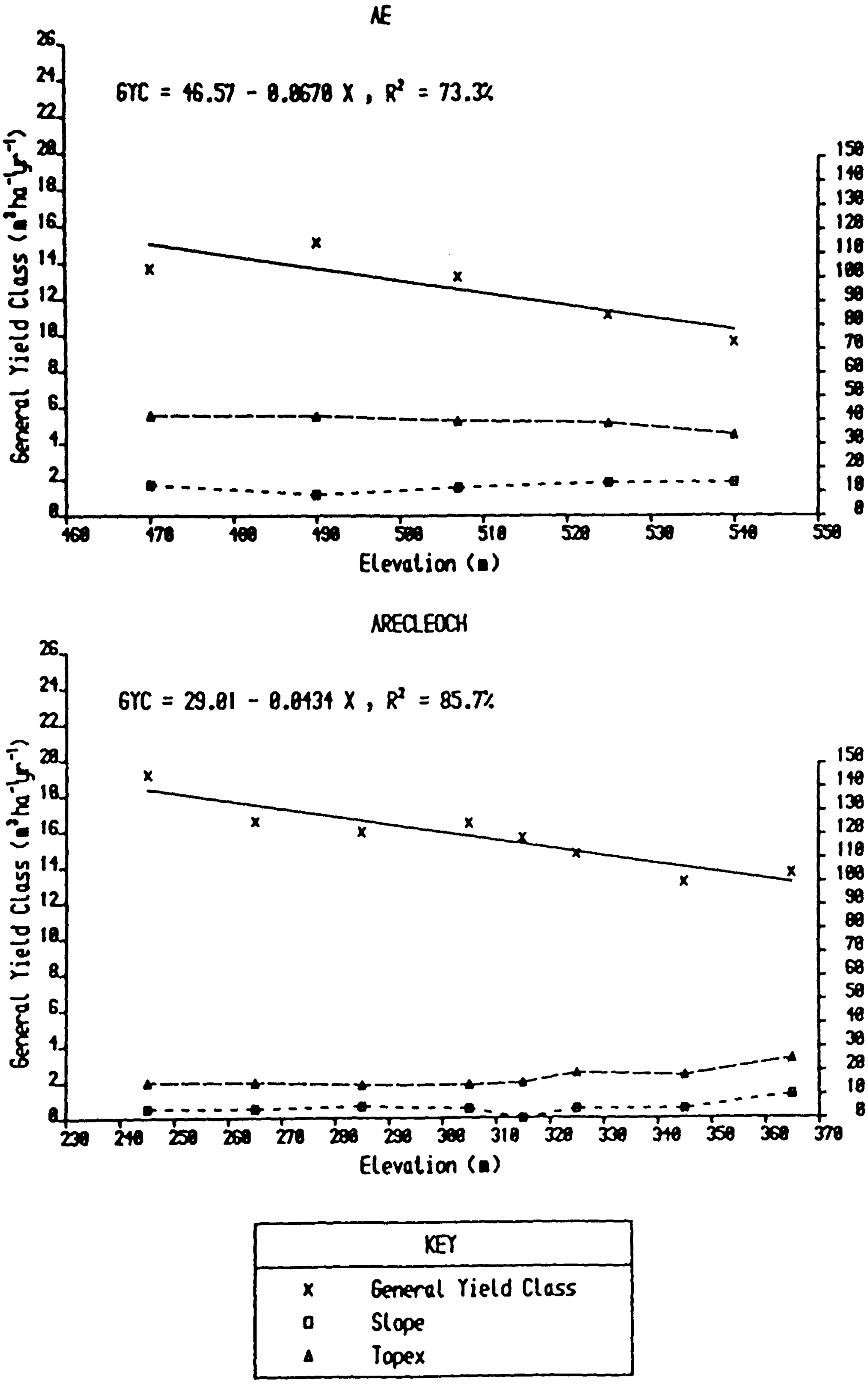


Figure 5a. Relationships between productivity (GYC) and elevation for the individual sites

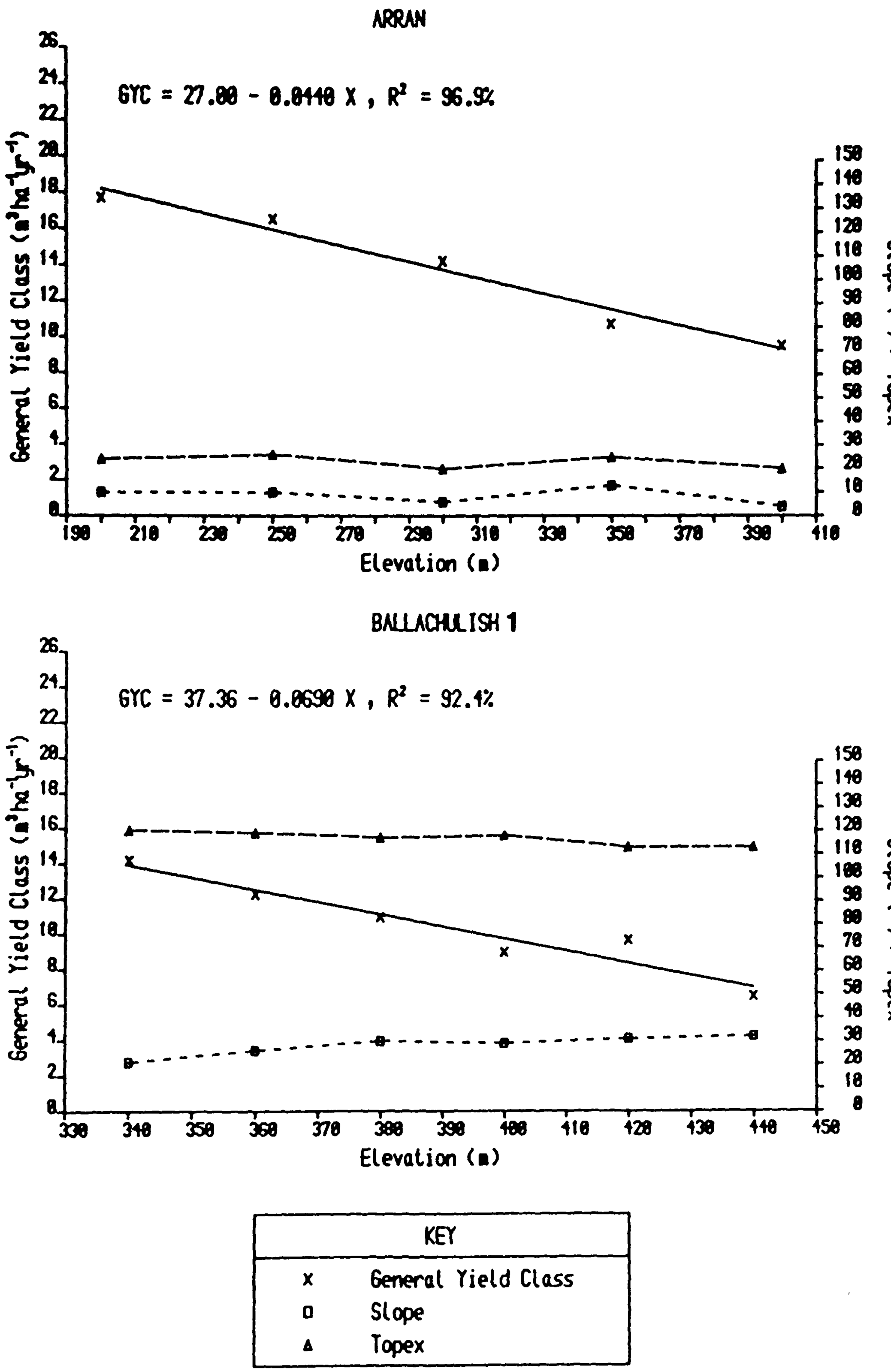
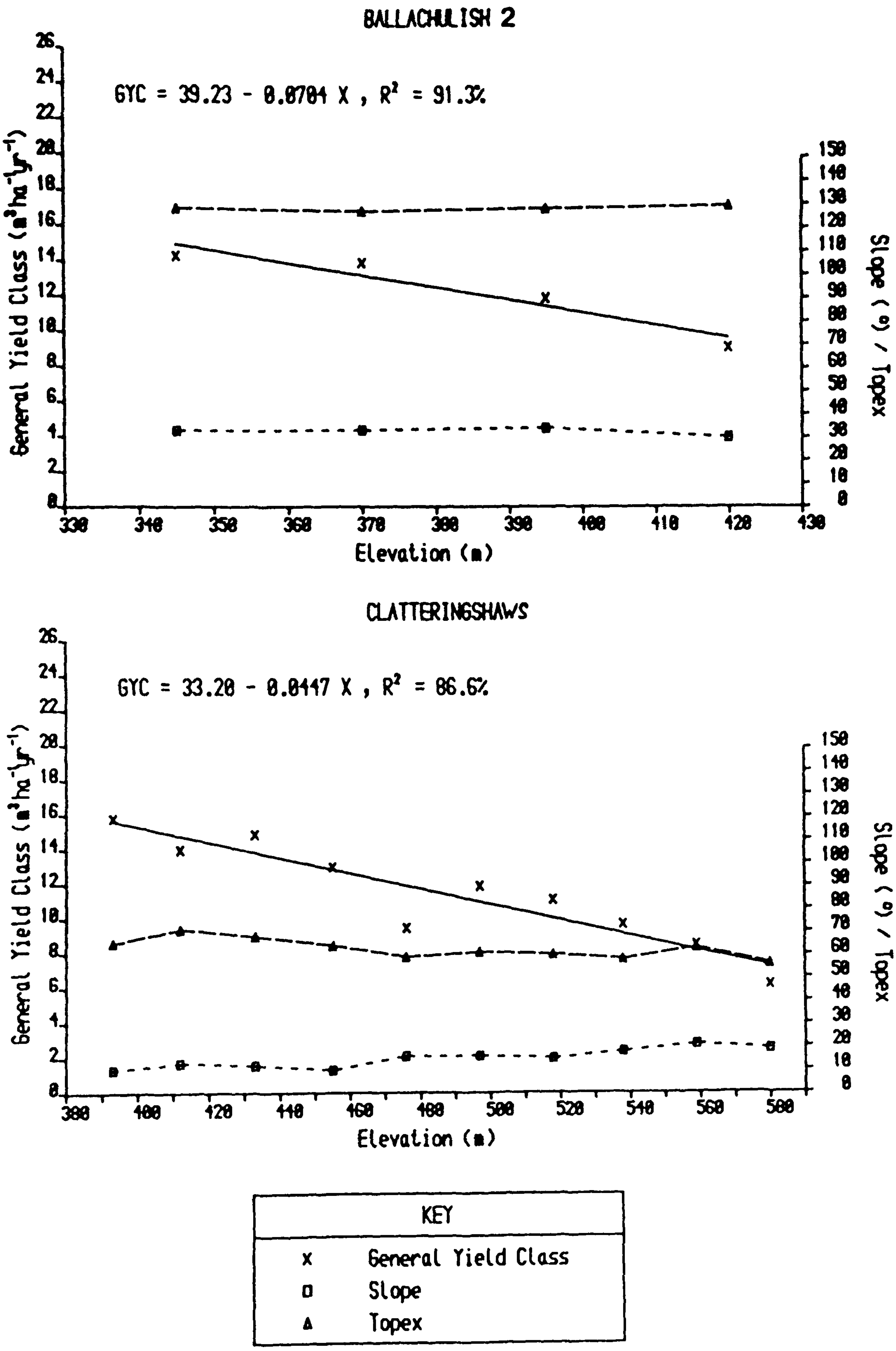

ARRAN
GYC = 27.00 - 0.0440 X , R² = 96.9%
General Yield Class (m³ha⁻¹yr⁻¹)
Slope (°) / Topex
Elevation (m)
BALLACHULISH 1
GYC = 37.36 - 0.0690 X , R² = 92.4%
General Yield Class (m³ha⁻¹yr⁻¹)
Slope (°) / Topex
Elevation (m)
KEY
x General Yield Class
□ Slope
▲ Topex

Figure 5b.



BALLACHULISH 2
GYC = 39.23 - 0.0704 X , R² = 91.3%
General Yield Class (m³ha⁻¹yr⁻¹)
Slope (°) / Topex
Elevation (m)
CLATTERINGSHAWS
GYC = 33.20 - 0.0447 X , R² = 86.6%
General Yield Class (m³ha⁻¹yr⁻¹)
Slope (°) / Topex
Elevation (m)
KEY
x General Yield Class
□ Slope
▲ Topex

Figure 5c.

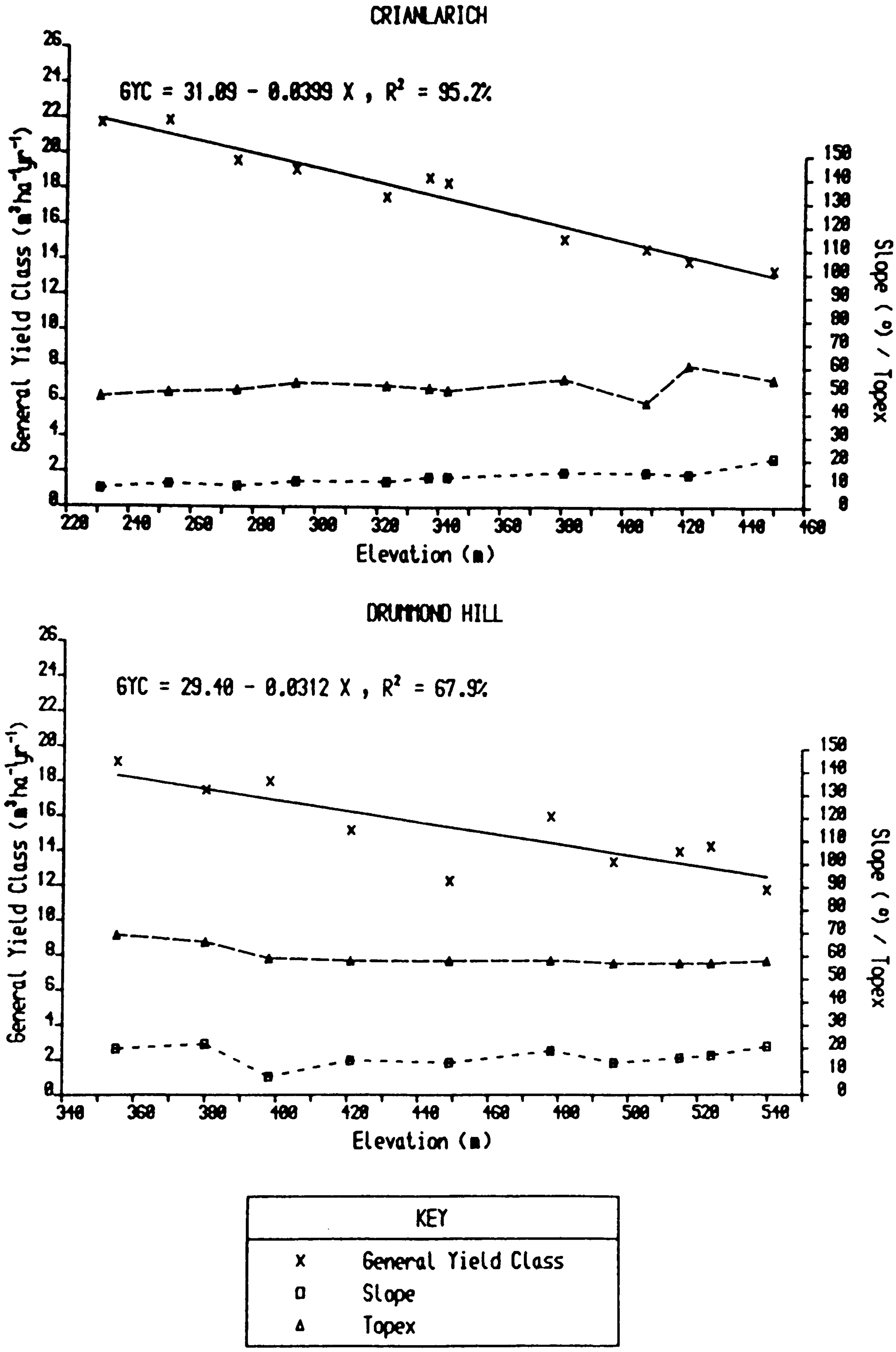
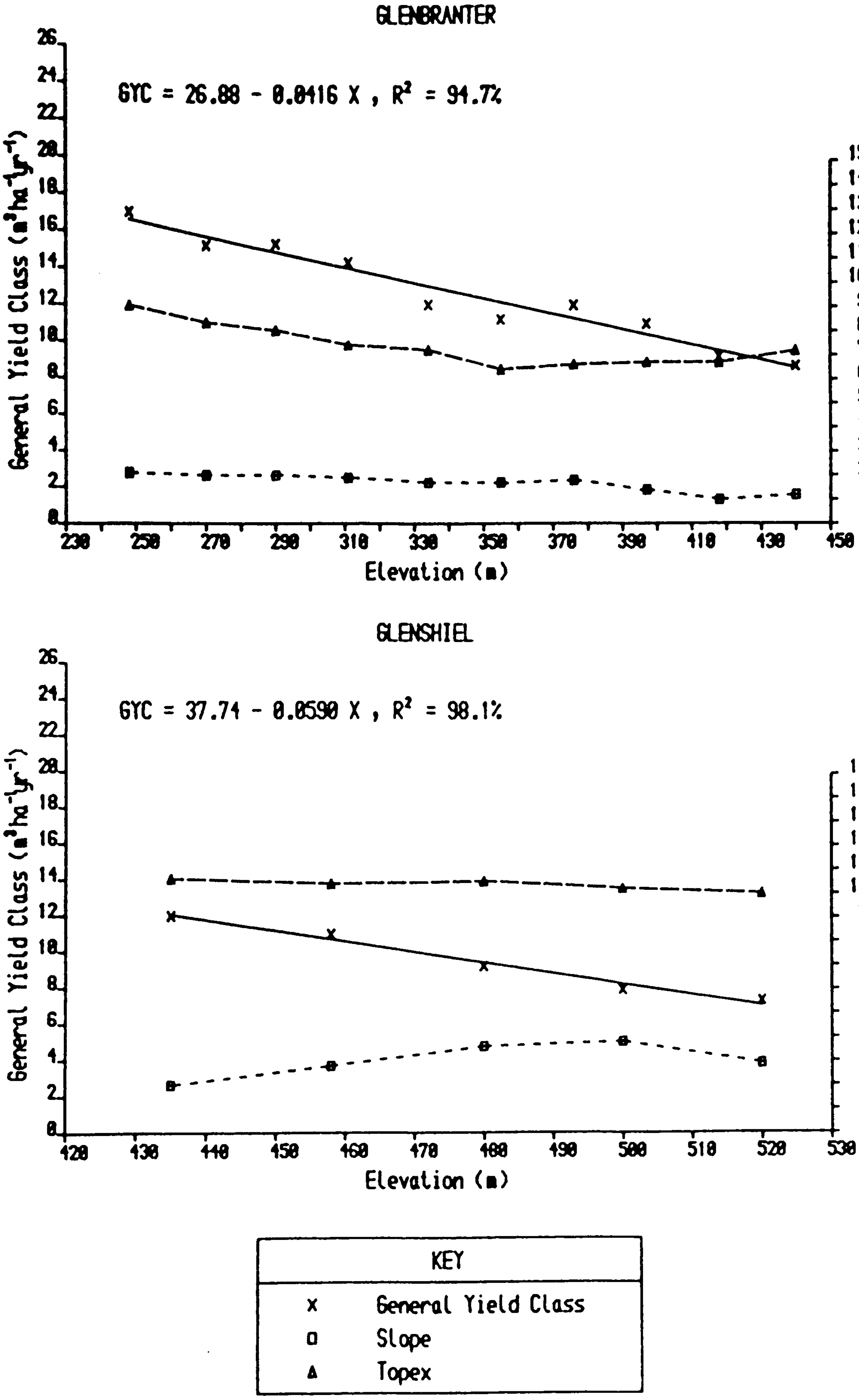

CRIANLARICH
GYC = 31.09 - 0.0399 X , R^2 = 95.2%
General Yield Class ($m^3ha^{-1}yr^{-1}$)
Slope (°) / Topex
Elevation (m)
DRUMMOND HILL
GYC = 29.40 - 0.0312 X , R^2 = 67.9%
General Yield Class ($m^3ha^{-1}yr^{-1}$)
Slope (°) / Topex
Elevation (m)
KEY
x General Yield Class
□ Slope
Δ Topex

Figure 5d.



GLENBRANTER
GYC = 26.88 - 0.0416 X , R² = 94.7%
General Yield Class (m³ha⁻¹yr⁻¹)
Slope (°) / Topex
Elevation (m)
GLENSHIEL
GYC = 37.74 - 0.0590 X , R² = 98.1%
General Yield Class (m³ha⁻¹yr⁻¹)
Slope (°) / Topex
Elevation (m)
KEY
x General Yield Class
□ Slope
▲ Topex

Figure 5e.

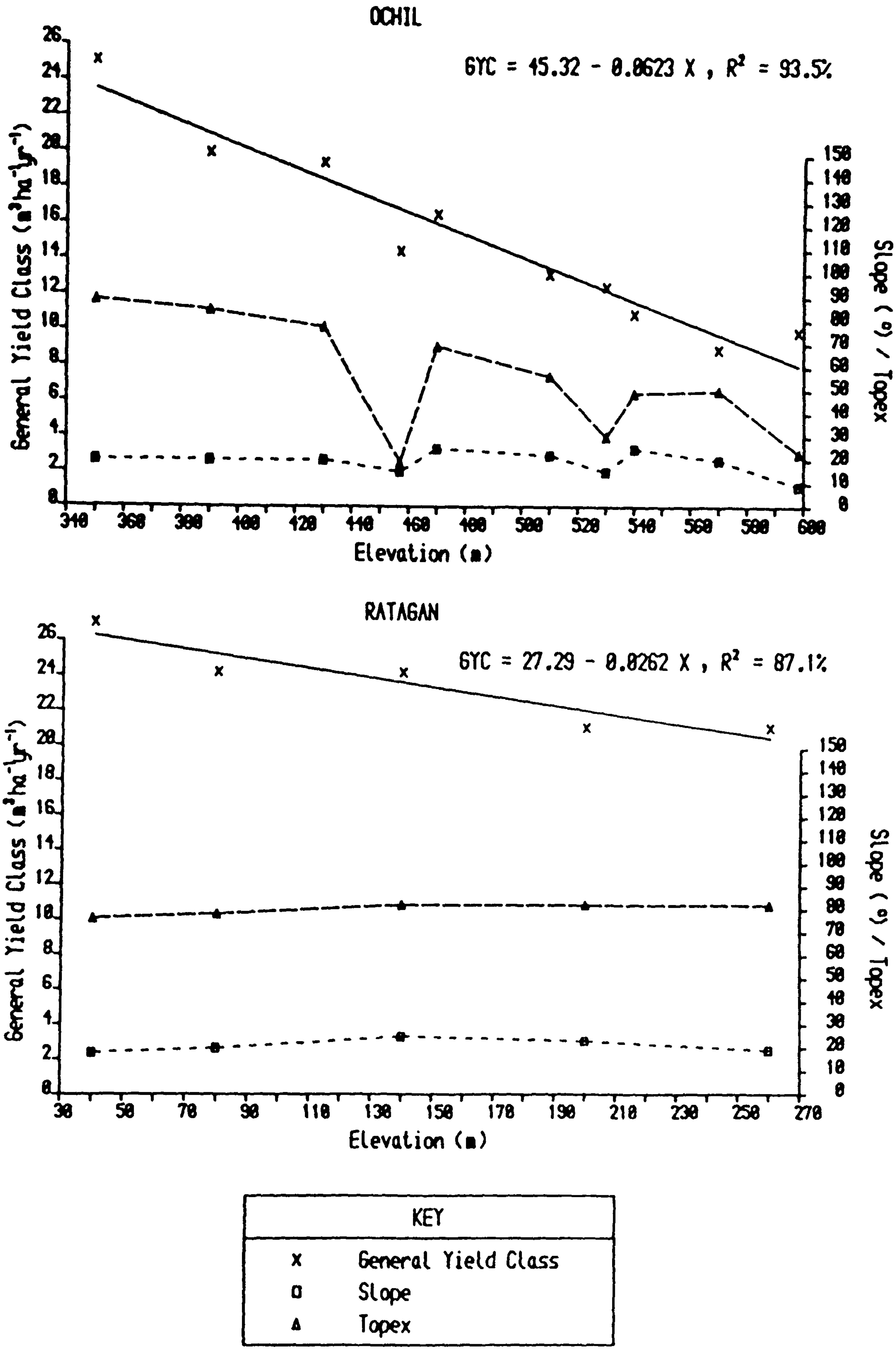

OCHIL
GYC = 45.32 - 0.0623 X , R² = 93.5%
General Yield Class (m³ha⁻¹yr⁻¹)
Slope (°) / Topex
Elevation (m)
RATAGAN
GYC = 27.29 - 0.0262 X , R² = 87.1%
General Yield Class (m³ha⁻¹yr⁻¹)
Slope (°) / Topex
Elevation (m)
KEY
x General Yield Class
□ Slope
Δ Topex

Figure 5f.

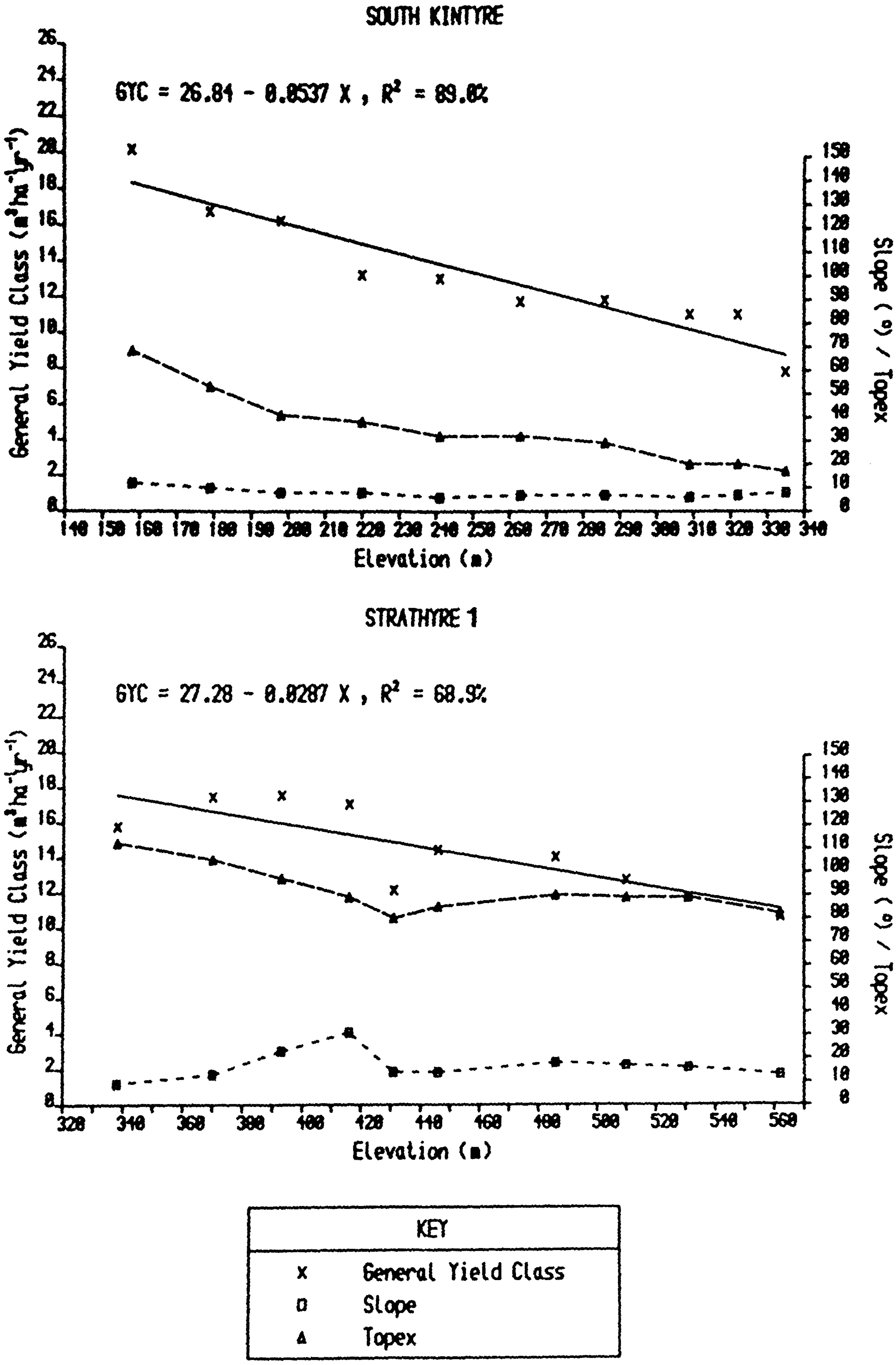
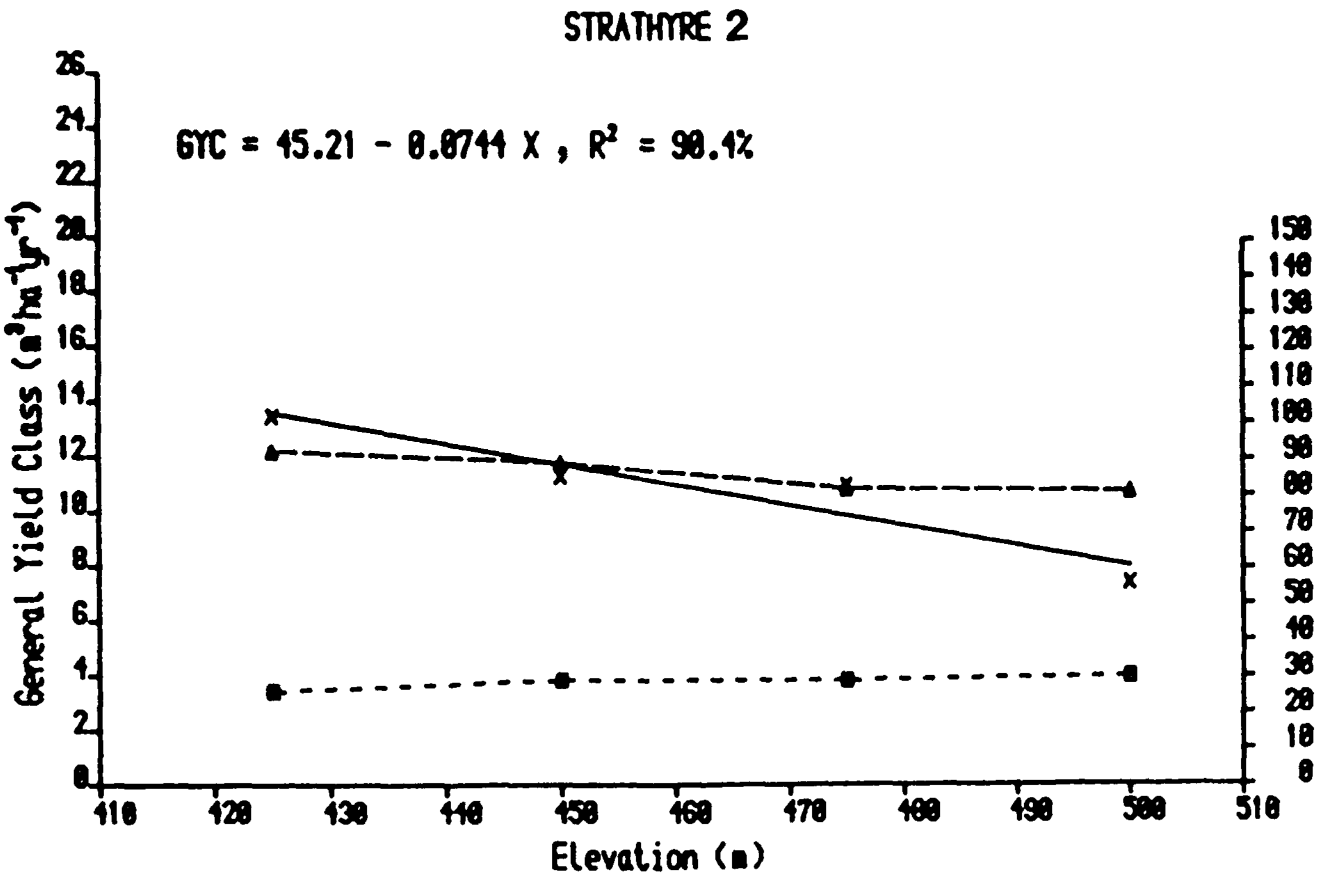
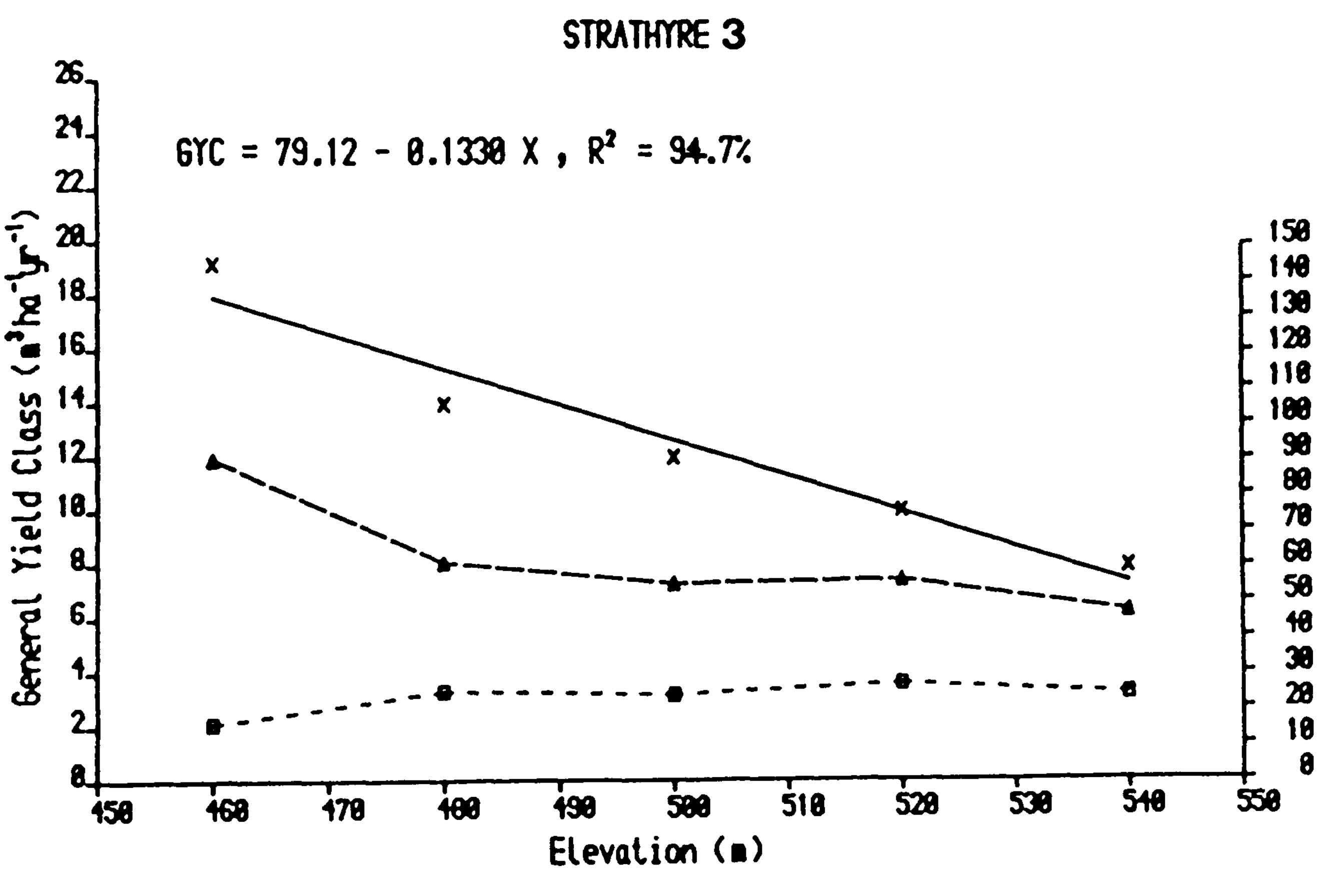

SOUTH KINTYRE
GYC = 26.84 - 0.0537 X , R² = 89.0%
General Yield Class (m³ha⁻¹yr⁻¹)
Slope (°) / Topex
Elevation (m)
STRATHYRE 1
GYC = 27.28 - 0.0287 X , R² = 68.9%
General Yield Class (m³ha⁻¹yr⁻¹)
Slope (°) / Topex
Elevation (m)
KEY
x General Yield Class
□ Slope
▵ Topex

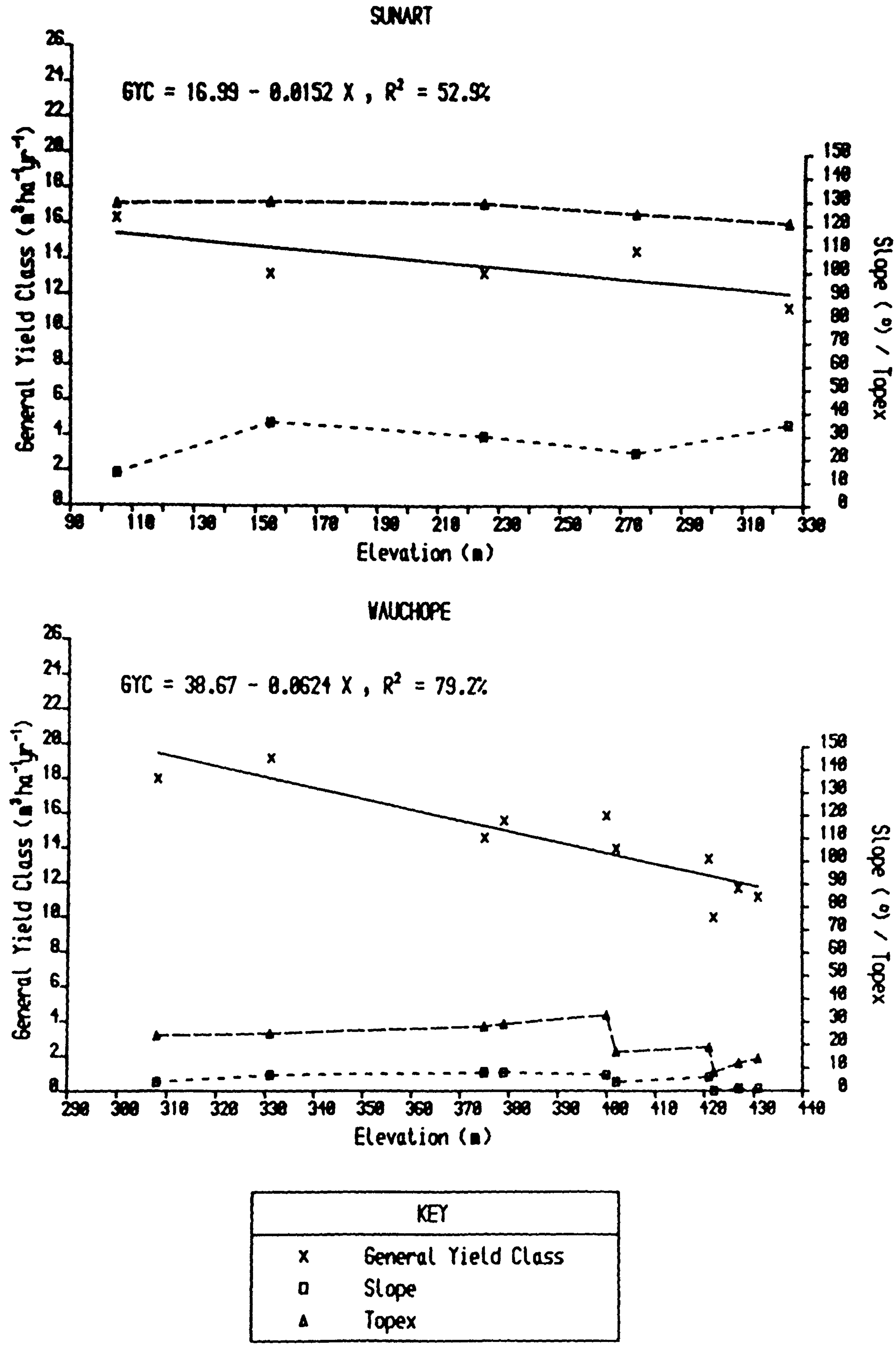
Figure 5g.





KEY	
x	General Yield Class
□	Slope
Δ	Topex

Figure 5h.



SUNART
GYC = 16.99 - 0.0152 X , R² = 52.9%
General Yield Class (m³ha⁻¹yr⁻¹)
Slope (°) / Topex
Elevation (m)
WAUCHOPE
GYC = 38.67 - 0.0624 X , R² = 79.2%
General Yield Class (m³ha⁻¹yr⁻¹)
Slope (°) / Topex
Elevation (m)
KEY
x General Yield Class
□ Slope
▲ Topex

Figure 5i.

sites which was aimed at avoiding areas with undue soil and topographic variability. The average rate of change in GYC with elevation was 4.3 m^3 ha^{-1} yr^{-1} per 100 m, with values varying between 1.7 m^3 ha^{-1} yr^{-1} and 7.4 m^3 ha^{-1} yr^{-1} and with one exceptional value of 13.3 (Strathyre 3). The relationships were best estimated by simple linear functions. Polynomial equations gave significantly better fit for the sites at Ae, Glenshiel and Strathyre 3. These sites had only 5 plots and the non-linear trends were often the result of one or two slightly aberrant GYC values.

3.2.2 Pooled data.

The relationship between GYC and elevation for the pooled data from all 188 plots was best estimated by a linear model. The equation was:

$$GYC = 20.3 - 0.0174(\text{elevation}) \quad r^2\ 36.1\% \quad ....(1)$$

The r^2 value of 36 per cent was lower than that recorded by Malcolm (1970) and Studholme (1968) but was higher than that of Mayhead and Broad (1978) for Wales. This relatively low r^2 value is largely accounted for by the fact that a very wide range of sites was sampled in this study compared with those of Malcolm and Studholme. A large amount of the variation in the overall GYC/elevation relationship is due to variation from site to site, as is apparent from Figure 6 which shows the regression lines for the individual sites together with the overall regression line for the pooled data.

Figure 6 also shows a clear disparity between the slopes of the regression lines for the individual sites (mean slope 0.0430) and the regression line for the pooled data (slope 0.0174). The slope of regression line for the pooled data is determined by both the GYC/elevation relationships for the individual sites and the variation in these relationships from site to site. Increasing elevation is associated with two trends in the GYC data:

1. A decrease in GYC on each site (within-site variation).
2. An increase in GYC associated with the fact that higher elevation sites tend to show higher GYC values at specific elevations than low level sites (between-site variation). This proved to be because there was a strong tendency for high level sites to be located in relatively sheltered inland areas and low-level sites to be located

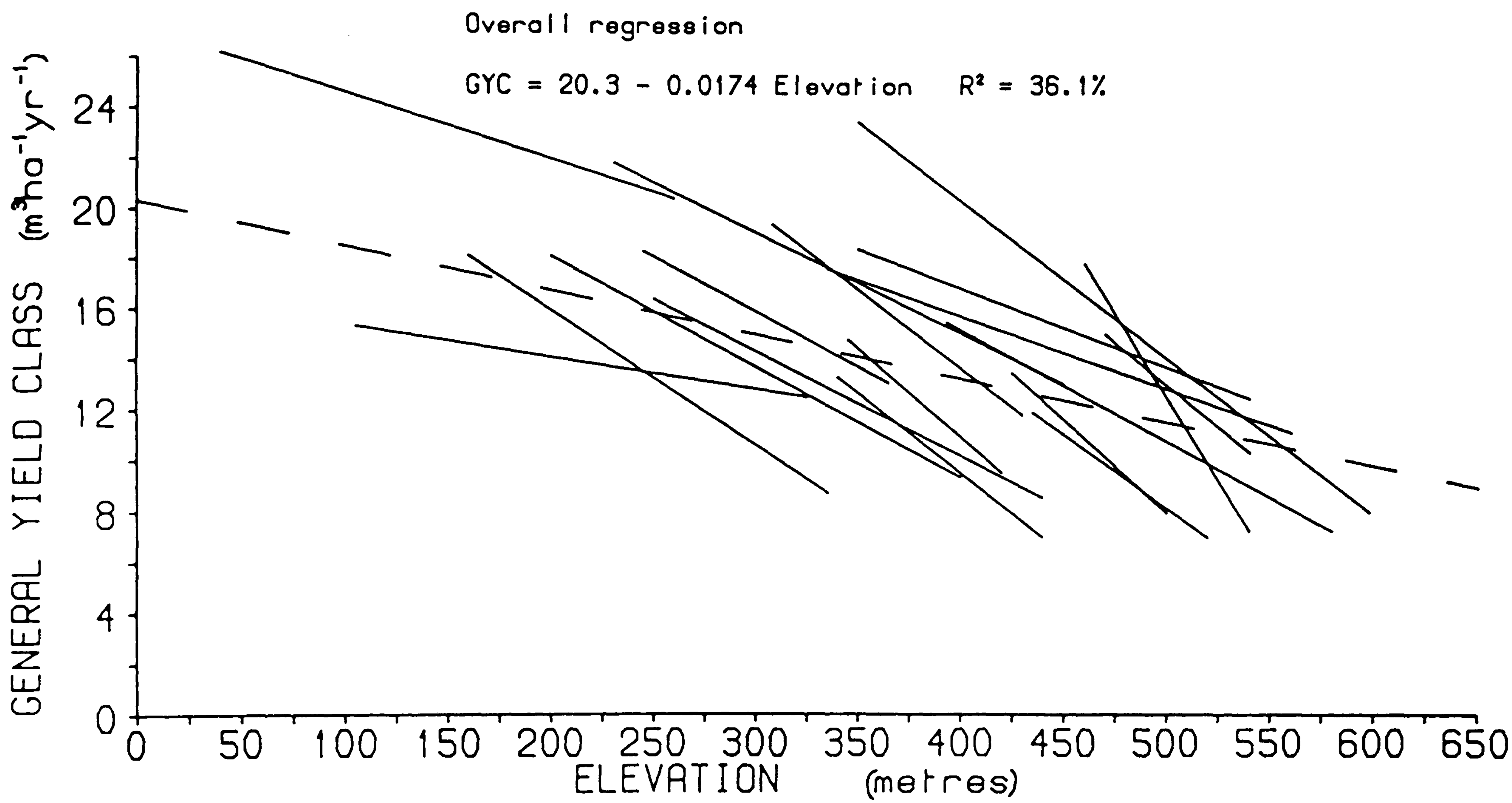


Figure 6. Relationship between productivity (GYC) and elevation for the pooled data

in more exposed coastal areas (see section 3.2.3).

3.2.3 Analysis of covariance.

A clearer picture of the trends described above was obtained by fitting a model in which a common slope was assumed for the GYC/elevation relationships, but GYC values were specific to each site (ie. the intercepts for the lines for each site were allowed to vary). This can be thought of as fitting an "average" regression line for the individual sites and then using the average displacement of the individual regression lines from this overall line as a measure of the effect of the site to site variation (ie. an analysis of covariance). This model was fitted for the data for the main sites by multiple regression analysis using dummy variables. Dummy variables provide an effective way of estimating the effects of categorical (qualitative) variables such as "site" (ie. location), which can be combined with metric (quantitative) variables in standard regression models (Nie. et al. 1975; see also Appendix 9 for a description of the use of dummy variables). The model used is shown below:

$$GYC = a + b(\text{elevation}) + b_1X_1 + b_2X_2 + \ldots\ldots\ldots b_nX_n$$

where $X_1, X_2, \ldots X_n$ are dummy variables taking values of 1 or 0

according to site.

Dummy variables are created by setting the value of, for example, X_1 for site 1 as 1.0 and all the other X-values to 0. For site 2, X_2 takes the value 1.0 and all the other X-values take 0. The entire set of dummy variables are then included in the regression analysis. In order to solve the normal equations, one of the sites must be a "reference category" for which the value of b is zero. Effectively all the other categories (sites) are compared with the reference category. In the case of this analysis the site at Glenbranter was the reference category. The data for the three sites at Strathyre and the two sites at Ballachulish were pooled to give a total of 15 sites. The resultant equation was:

$$GYC = 27.3 - 0.043(\text{elevation}) + \text{"site effects'} \quad \ldots\ldots\ldots \quad (2)$$

The values of the coefficients $b_1, b_2 \ldots b_n$ (ie. the "site effects") varied from -4.32 $m^3\ ha^{-1}\ yr^{-1}$ to 8.57 $m^3\ ha^{-1}\ yr^{-1}$ and are shown in Figure 7 (see Appendix 2a for regression analysis). A tendency for inland sites to have the highest values is apparent. The effect of location was highly significant, with a f-value of 27.5

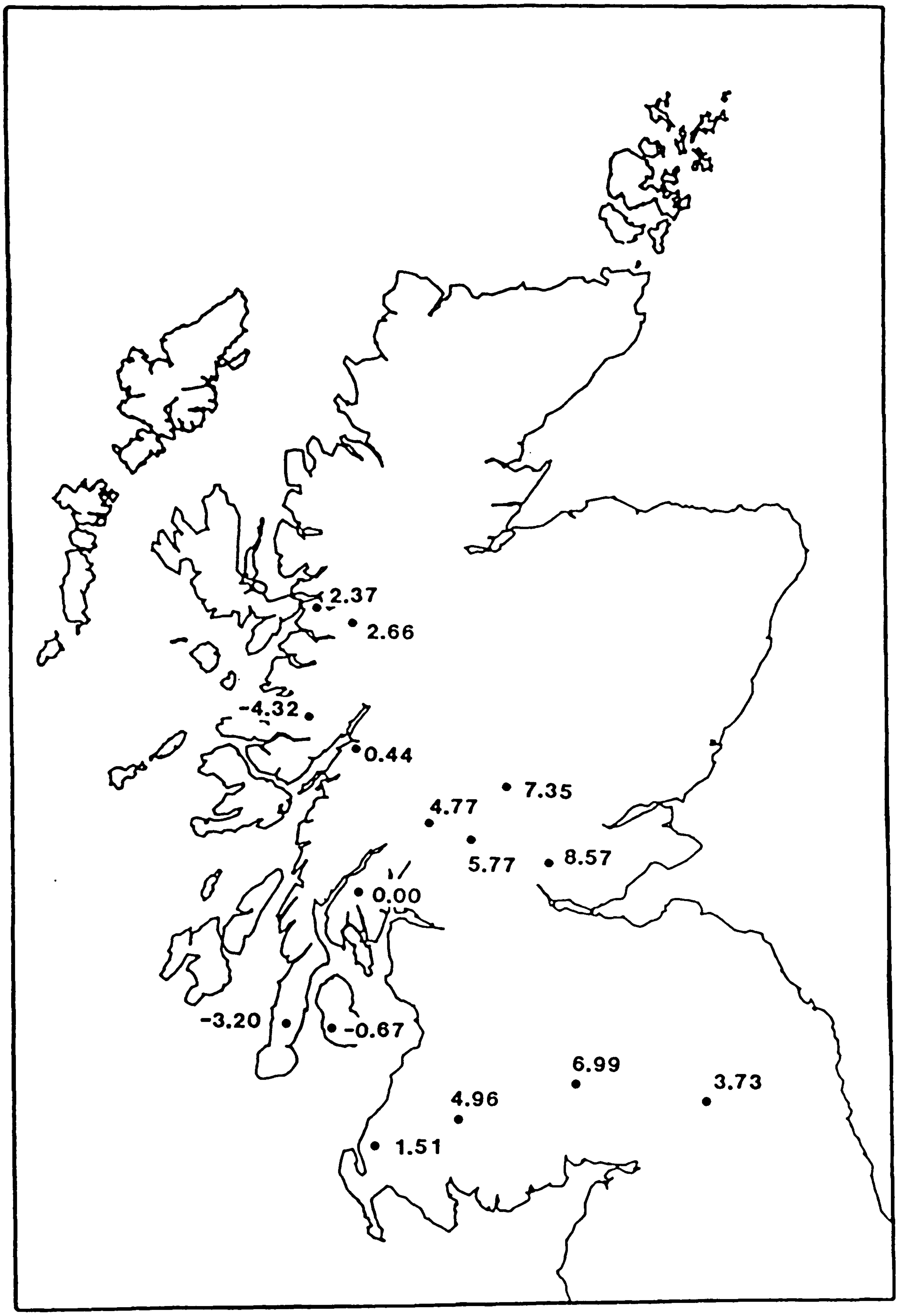


Figure 7. Site effect coefficients for the major sites

(see Appendix 2a). This f-test effectively tests the hypothesis that there is no difference between the intercepts for the individual sites assuming a common slope to the GYC/elevation relationships.

This model was then fitted for the entire data set to investigate the geographical distribution of the variation in the GYC/elevation relationships. This gave the following equation:

GYC = 26.5 - 0.0404(elevation) + "site effect" .... (3)

$r^2 = 80.7\%$

The site effects varied between -9.45 and +8.34 $m^3\ ha^{-1}\ yr^{-1}$ with the lowest values being recorded in western and northern coastal areas and the highest in inland and southern areas (see Appendix 2b). The site effects were contour mapped by computer as shown in Figure 8 to give an overall impression of the effect of geographical location on GYC.

The "site effects" were also clearly related to the mean elevation for each site (Figure 9) with the values of "site effect" increasing by on average 2.4 $m^3\ ha^{-1}\ yr^{-1}$ for every 100 m increase in elevation. This means that an increase in elevation of 100 m, as well as being associated with a decrease in GYC of 4.3 $m^3\ ha^{-1}\ yr^{-1}$ is, in this data set, also associated with an increase in GYC of about 2.5 $m^3\ ha^{-1}\ yr^{-1}$ as one moves inland and southwards.

Reference to Figure 8 and equation (3) above provides a simple method of estimating GYC for any area of Scotland at any elevation within the original range of the data. For example the GYC at 400 metres at Glenbranter is estimated to be:

GYC = 26.5 - 0.0404(400) + 0.0 = 10.3 ie. GYC 10

At 400 metres in Caithness the GYC is estimated to be:

GYC = 26.5 - 0.0404(400) - 4.0 = 6.3 ie. GYC 6

At 400 metres over much of central Scotland GYC is estimated to be:

GYC = 26.5 - 0.0404(400) + 4.0 = 14.3 ie. GYC 14

The tendency for value of GYC at specific elevations to be lower in coastal and northern areas than in inland areas is readily apparent from Figure 8. The pattern is remarkably similar to that described as "exposure zones" by Anderson (1930), which were essentially arrived at in a similar fashion but

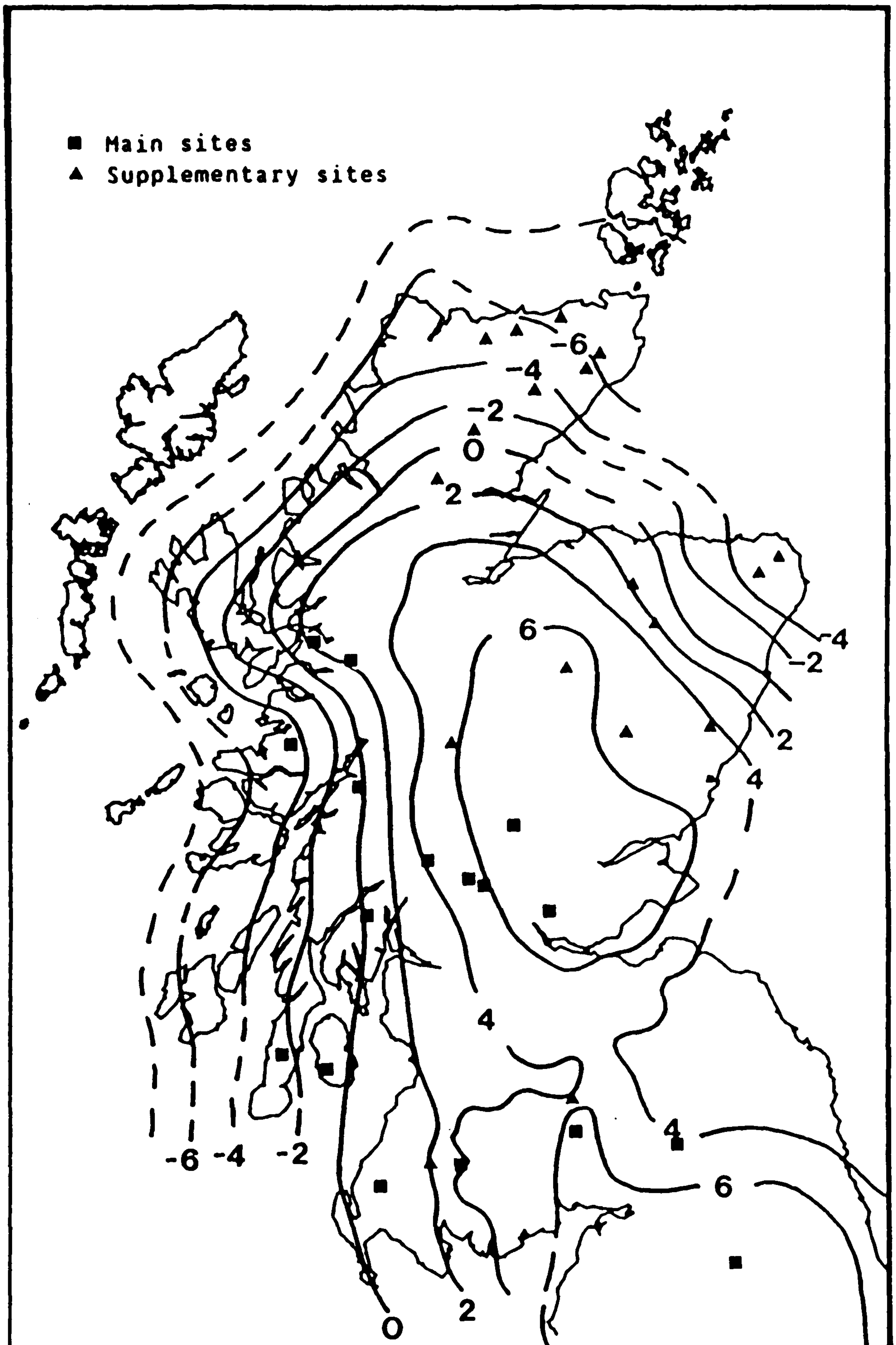


Figure 8. Site effect coefficients for all the sites

without the aid of statistical analysis. The pattern also clearly resembles known patterns of windiness such as mean windspeeds (Hardman et al. 1973) and Forestry Commission windzones (Miller 1985). It is also similar to the distribution of growing season temperature in Scotland (Meteorological Office 1952).

Models 2 and 3 assume that although the intercepts of the individual GYC elevation relationships vary from site to site, their slopes are the same. The hypothesis that the slopes were the same was tested by comparing the model (2) above with a model (4) in which both the slopes and the intercepts were free to vary (ie. essentially a summation of the regression analyses for all the individual major sites - see Appendix 3). The f-ratio for:

$$\frac{[\text{SS res.}_2 - \text{SS res.}_4]/[\text{d.f. res.}_2 - \text{d.f. res.}_4]}{\text{MS res.}_2}$$

= 3.33 ** (see Appendix 3)

where:

SS res._2 = sum of squares of residual for model 2 etc.

d.f. res._2 = degrees of freedom for residual for model 2 etc.

MS res._2 = mean square residual for model 2.

This result indicates that the slopes of the regression lines for the individual sites are not the same.

Figure 10 shows the relationship between the slopes of the regression lines for the individual sites and the mean elevation of the sites. A tendency for the slopes of the lines to increase with elevation is apparent, though this trend is conditioned to a large extent by values at the upper and lower extremes of elevation. A similar trend can be seen by comparing the results of Studholme (1968), who sampled sites at high elevations and recorded a rate of decrease in the GYC of Sitka spruce of 6.6 m^3 ha^{-1} yr^{-1} per 100 m, with those of Malcolm (1970) who sampled the entire elevation range and recorded a rate of about 2.8 m^3 ha^{-1} yr^{-1}.

This indicates that the underlying trend in the GYC/elevation relationship may be non-linear, with greater rates of decrease in GYC with elevation occurring at higher elevations. To test for this a quadratic model was fitted with "site effects" estimated by using dummy variables as in model (2) above.

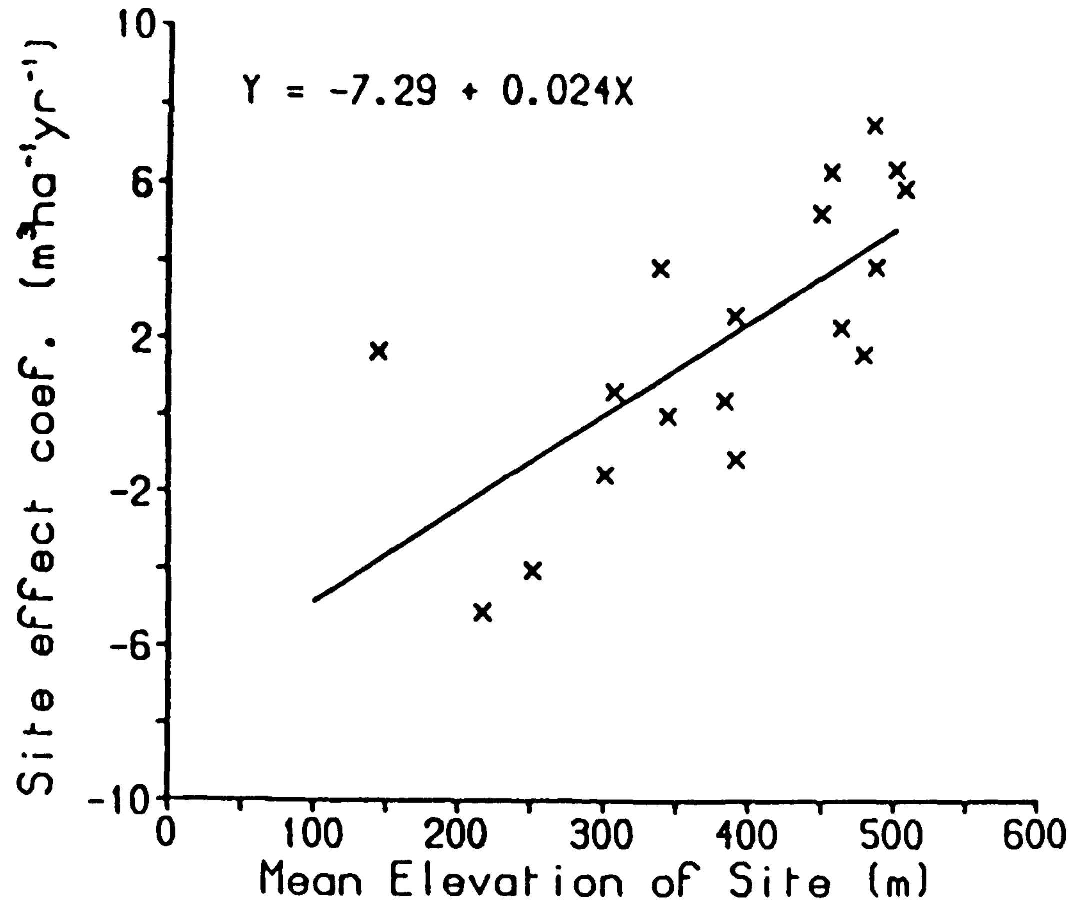


Figure 9. Relationship between site effect coefficients for the major sites and mean elevation for the sites

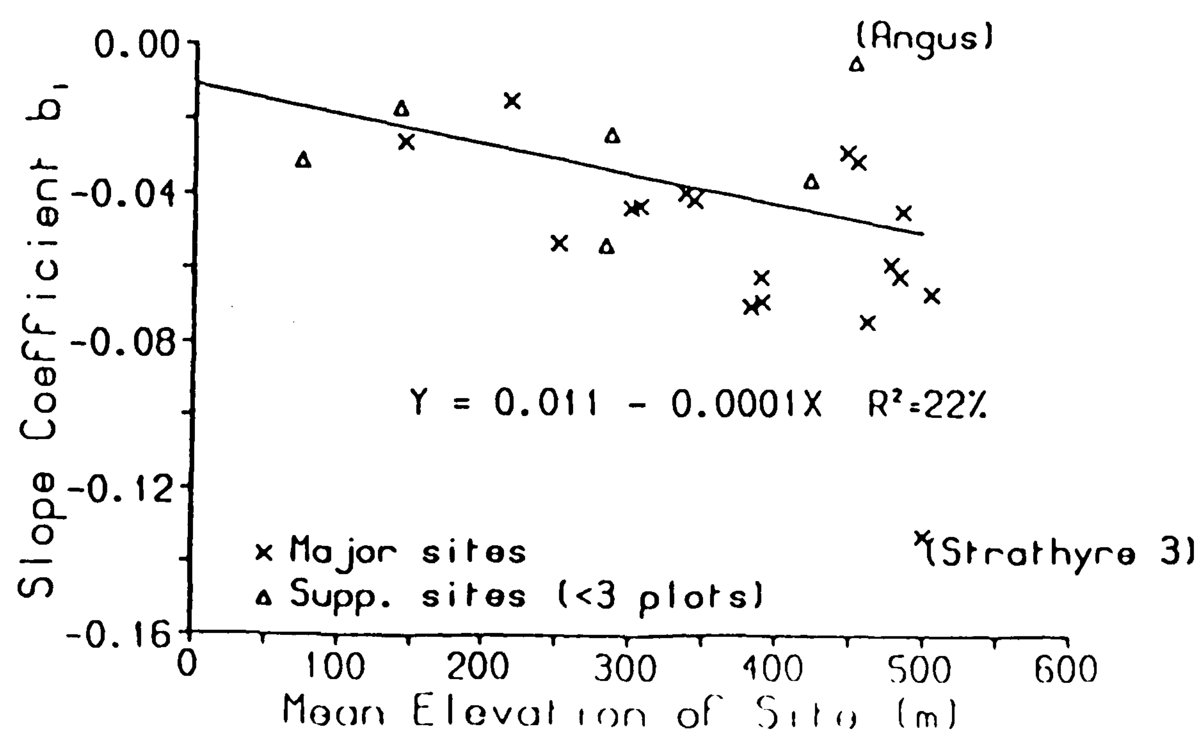


Figure 10. Relationship between the slope coefficient for all the sites and the mean elevation for the sites

This model was fitted for both the data for the main sites and for the complete data set. The resultant equations were:

Main sites

$$GYC = 27.4 - 0.0224(\text{elevation}) - 0.0000282(\text{elevation}^2) + \text{"site effect"}$$

$$r^2 = 88.5\% \quad ..... \text{(model 5)}$$

Complete data

$$GYC = 24.4 - 0.0262(\text{elevation}) - 0.00001973(\text{elevation}^2) + \text{"site effect"}$$

$$r^2 = 81.1\% \quad ..... \text{(model 6)}$$

The site effects for for the complete data set were contour-mapped by computer (Figure 11.). The effect of the quadratic term was significant ($P <$ 0.001) for the data for the main sites but was not significant for the complete data set. The fact that the quadratic term was not significant for the complete data set was found to be largely due to the effect of the data for the site at Angus which did not conform to the pattern of greater values for the slope coefficient at higher elevations (see Figure 10). The plots at Angus were located on old tatter flag sites and the highest elevation plot (number 134 - see Appendix 1) appeared to be showing unrepresentatively high growth rates for the area. When data for this site were excluded the effect of the quadratic term was significant ($P < 0.05$).

These results indicate that the underlying trend of decreasing GYC with increasing elevation may be non-linear over the entire elevation range. The fact that the GYC/elevation relationships at the individual sites were generally best estimated by linear models indicates that the elevation ranges sampled were too small for any non-linear trend to be detected. It should be noted that GYC data was not collected over the entire elevation range at any site during this study, so models 5 and 6 above do not give a particularly good estimate of the curvilinear trend. Malcolm (1970), although finding that a linear model gave a good fit when his and Studholme's (1968) data were combined, noted that there was "an indication that the rate of reduction in growth with increasing elevation is accelerating towards the higher elevations".

Further evidence for a non-linear trend to the GYC/elevation relationship is apparent from the fact that most of the linear functions shown in Figures 5a-i give overestimates of GYC when extrapolated beyond the range of the data to

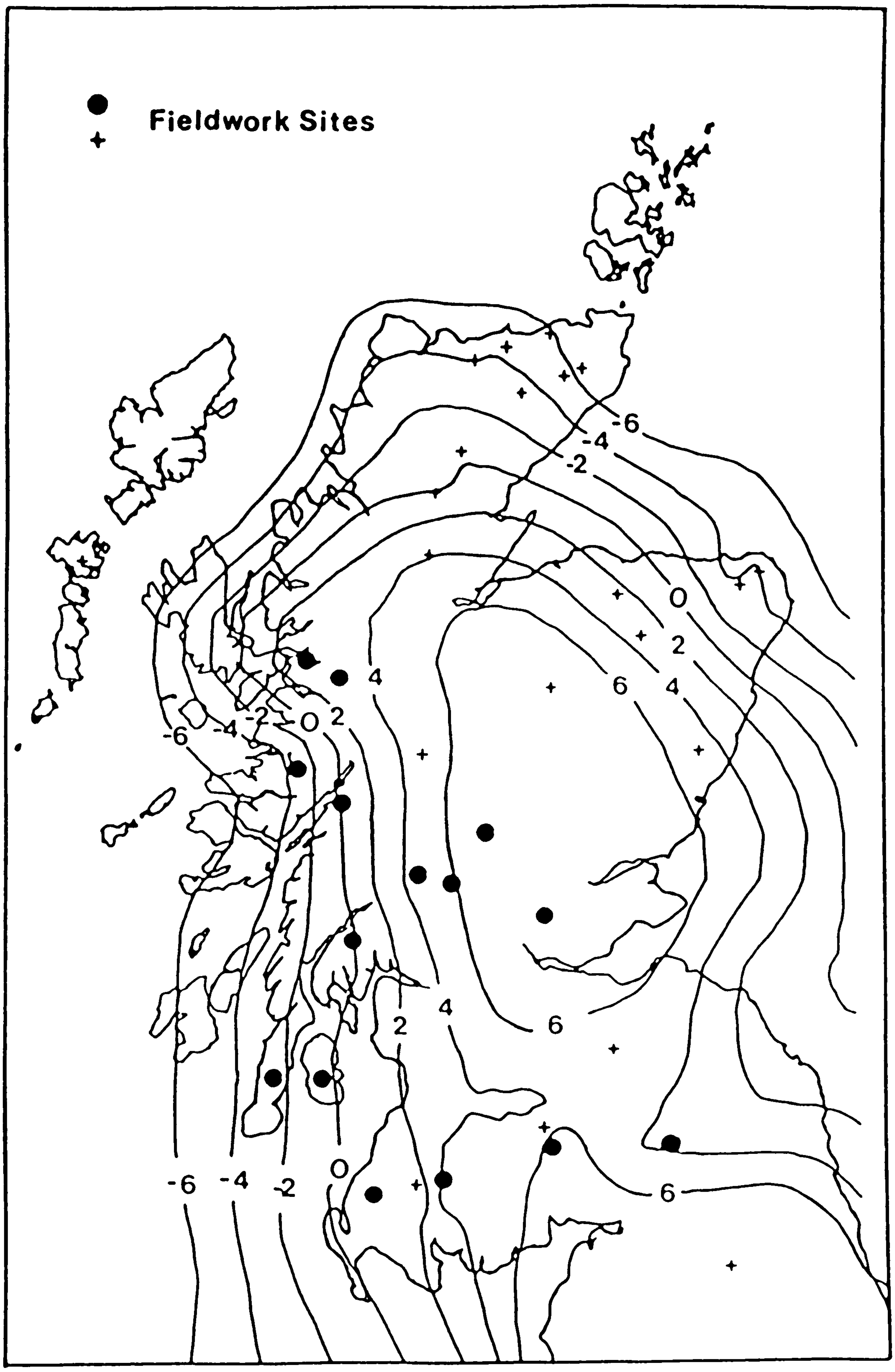


Figure 11. Site effect coefficients for model 6

low values of elevation. The average value of the intercept coefficient (GYC when elevation = 0) was GYC 31. Values of GYC in excess of 20 to 24 are comparatively infrequent in northern Britain, though they are known to occur. This indicates that the rates of increase in GYC with decreasing elevation recorded on the exposed sites in this study are not sustained over the entire elevation range. This is particularly true of inland sites.

This apparent non-linear trend may be the result of the environmental factors which affect growth such as site windiness, temperature or soil conditions changing more rapidly with elevation at high elevations and on exposed sites than at low elevations. Alternatively productivity at lower elevations could be limited by moisture supply (Jarvis et al. 1983), so that decreases in GYC due to increasingly adverse wind, temperature and edaphic conditions only begin to operate at elevations where moisture supply ceases to be a limiting factor. The soils and moisture regimes of the sites in this study were particularly favourable for the growth of Sitka spruce and it is possible that if such site conditions existed at low elevations in sheltered locations, then GYC values of near 30 may be more realistic. It is worth noting in this context that while growth rates of GYC 20-24 are commonly the maximum for lowland sites in the United Kingdom, values as high as 36 occur on certain low-level sites in wet areas of Ireland (Davis 1982)

Even though there is evidence for an underlying non-linear relationship between GYC and elevation over the *entire* elevation range, over the restricted elevation ranges on the individual sites the relationships were generally best described as linear functions. For this reason it was felt that linear models such as models (2) and (3) were appropriate for describing the relationships between GYC and elevation for the restricted elevation ranges of the exposed sites surveyed in this study. Further research is needed to clarify the nature of the relationship between GYC and elevation on low elevation sites.

3.3 Planting limits.

Table 4. shows the elevations at which GYC 6 and GYC 8 and GYC 10 are predicted to occur according to the functions for the individual sites. GYC 6 was chosen as it is the lowest productivity level for which yield tables have been published. GYC 8 is the lowest yield class generally considered acceptable on economic grounds in Britain and GYC 10 has been suggested as

Table 4. Elevation in metres at which GYC 6 and GYC 8 are predicted by the linear functions for the main sites.

SITE	WINDZONE	ELEVATION GYC=6	ELEVATION GYC=8	ELEVATION GYC=10
South Kintyre	B	387	350	313
Ratagan*	B (?)	(665)	(601)	(537)
Arran	C	477	432	387
Arecleoch	C	530	483	436
Sunart*	C	(723)	(592)	(461)
Ballachulish 1	C/D	455	426	397
Ballachulish 2	C/D	471	443	415
Ae	D	606	576	540
Clatteringshaws	D	609	564	519
Glenbranter	D	502	454	406
Glenshiel	D	537	503	469
Wauchope	D/E	524	492	460
Crianlarich	E	629	579	529
Drummond Hill	E	750	686	622
Glendevon	E	631	599	567
Strathyre 1	E	750	672	594
Strathyre 2	E	527	500	473
Strathyre 3	E	550	535	520

* particularly unreliable values due to extrapolating well beyond the range of the data.

? boundaries of windzones particularly uncertain in this area due to lack of tatter flag data.

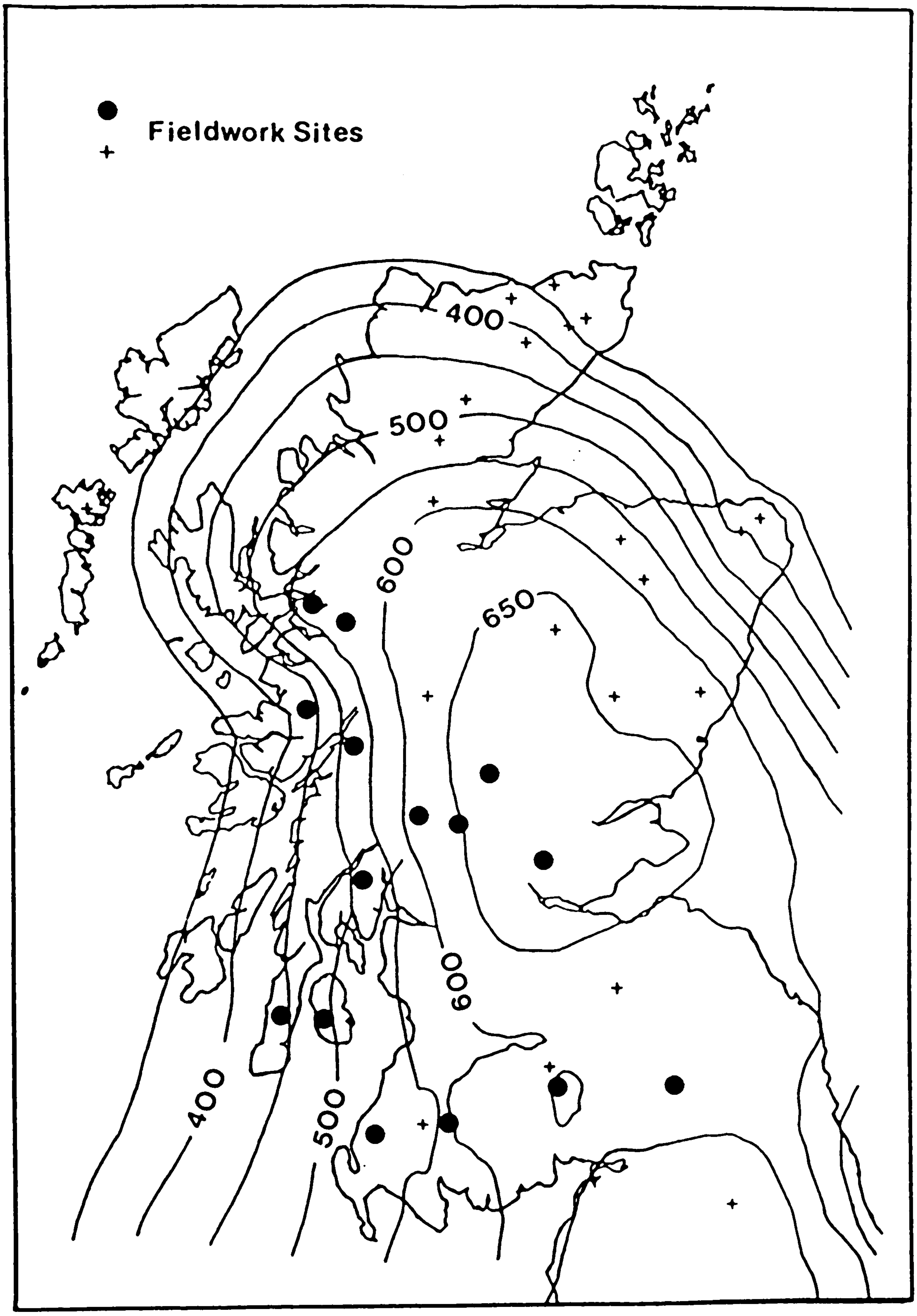


Figure 12. Elevation at which GYC 8 is predicted by model 7

a suitable minimum on remote sites (Gale and Anderson 1984).

The elevation at which GYC 8 is predicted varied from 350 m for the site at South Kintyre to over 600 m for several of the inland sites. Values for the sites at Ratagan and Sunart were generated by extrapolating well beyond the range of the original data and are clearly aberrant. At both these sites only 5 plots were sampled and low rates of decrease in GYC with elevation were recorded.

With the exception of these two sites the data show a tendency for the planting limit to rise according to windzone (ie. from coastal to inland locations - see Appendix 10 for wind zone map). This pattern is illustrated in Figure 12 which shows the values of elevation predicted for GYC 8 by transposing model (3) above to:

Elevation of planting limit = (26.5 - 8.0 + "site effect")/0.0404 ...(7)

The values predicted for each site were mapped by computer. The values predicted range from 300 m for the outer part of the west coast to over 600m in several inland areas. These agree well with previous estimates of yield classes near upper planting limits. For example, Gale and Anderson (1984) estimated that GYC 8-10 occurred between 520 and 560 m in Galloway (550 m predicted by equation (2)) and Patterson (1977) estimated planting limits to be 550 m in Upper Deeside (550-600 m predicted by equation (2)).

3.4 Conclusions.

1. Production (ie. General Yield Class) is fairly closely related to elevation on the individual sites (see Figures 5a-i).

2. There is considerable variation in the relationships between GYC and elevation from site to site, coastal and northern sites showing lower levels of productivity at specific elevations than inland and southern sites.

3. The geographical distribution of the differences in the GYC/elevation relationships from site to site is similar to known pattern of windiness and temperature.

4. The relationships between General Yield Class and elevation is linear on all but three sites, but the slopes of the regression lines for the individual sites tend to increase as the mean elevation of the sites increase. This indicates

that the underlying trend of decreasing productivity with increasing elevation is non-linear for the entire elevation range.

5. A simple model has been developed in which GYC is related to elevation and geographical location (model 3). This allows the rough estimation of general yield class at specific elevations on exposed sites for any area of Scotland and parts of northern England. By assuming a minimum acceptable GYC value of, for example, GYC 8 estimates of upper planting limits can also be made.

On account of the patterns described in conclusion 3. above, investigation of the roles of wind and growing season temperature on the productivity of Sitka spruce on exposed sites was carried out.

CHAPTER 4

THE EFFECTS OF TEMPERATURE AND WIND ON PRODUCTIVITY.

4.1 Introduction.

4.1.1 Temperature and forest productivity.

Temperature has been shown to affect the growth and productivity of forests (Mikola 1962, Farr and Harris 1979), the growth of individual forest trees both natural and planted (eg. Hiley and Cunliffe 1922, Baldwin 1931, Dahl and Mork 1959, Millar 1965, Cleary and Waring 1969, Perala 1985) and of potted trees in controlled experiments (eg. Tranquillini 1979, Freezaillah 1974). It also influences the yield of pasture (eg. Hunter and Grant 1971) and the growth rates of natural vegetation (eg. Grace and Woolhouse 1970). As well as affecting the productivity of trees, temperature also affects the distribution of tree species, their flowering and fruiting and their cycle of dormancy and budbreak. Temperature is a particularly critical factor in the growth and reproduction of alpine and arctic forests, and has a dominating influence on the occurrence of treelines (Toumey 1947, Daubenmire 1954, Mikola 1962, Tranquillini 1979).

The effects of temperature on the growth of trees are complex because temperature affects the rate of almost every physiological process in plants. These include photosynthesis (source activity) and respiration and the utilisation of assimilates for growth and storage (sink activity). The rates of cell division and expansion which are fundamental to the growth process are also affected, as are transpiration and the translocation of substances including nutrients and hormones. At the cellular level increasing temperature leads to increased rates of chemical reaction until the temperatures become high enough to inhibit enzyme activity, after which reaction rates of enzyme mediated reactions decline (Fitter and Hay 1981). This is reflected in the existence of temperature optima for several plant processes including photosynthesis and growth rates (eg. Hellmers et al. 1970, Neilson et al. 1972, Håbjörg 1972, Pymar 1978). For example Sitka spruce showed maximum extension growth when under a regime of 20 °C by day and 8 °C by night (Pymar 1978). Temperature optima for growth and photosynthesis in conifers generally lie in the range 15-25 °C . Such temperatures prevail for only a relatively small proportion of the time on upland sites in Britain, from which it can be concluded that temperature is likely to be a major limiting factor for tree growth in the British uplands.

4.1.1.1 Primary production.

The relationships between environmental factors and the primary production of coniferous trees has been reviewed by Tranquillini (1979). Trees in common with other plants show a characteristic pattern of increasing net photosynthesis with increasing temperature up to a maximum which is commonly in the range 15 - 30 °C for temperate species. Beyond this optimal temperature net photosynthesis declines. The minimum, optimum and maximum temperatures for net photosynthesis are species specific, as are the overall values of rates of photosynthesis (Fitter and Hay 1981). Neilson et al. (1972) showed that the temperature optimum for Sitka spruce lay in the range 10 - 20 °C but was generally about 18 °C. Rates of photosynthesis decline to zero at about -5 °C.

Temperature optima (and minima) for photosynthesis generally decrease with increasing altitude, which possibly indicates a degree of adaption to high elevation sites (Fryer and Ledig 1972, Slayter and Morrow 1977, Tranquillini 1979, Tranquillini and Havranek 1985). Tranquillini and Havranek reported a strong negative correlation between temperature optima and elevation of origin in Norway spruce. The lapse rate of the temperature optimum was 0.2-0.65 °C per 100 m. Similar effects have been noted in European larch and Norway spruce (Tranquillini 1979), *Betula verrucosa* (Pisek et al. 1969), and *Eucalyptus pauciflora* (Slayter and Morrow 1977).

Many conifers can photosynthesise at temperatures below 0 °C and at low elevations even in continental areas net carbon assimilation during the winter may be positive (Pisek and Tranquillini 1954, Tranquillini 1979). According to Neilson et al. (1972) net photosynthesis in Sitka spruce at 0 °C under high illumination proceeds at over 30 per cent of the maximum value. This means that photosynthetic dormancy in Sitka spruce in Scotland must be infrequent and transient (Neilson et al. 1972). Bradbury and Malcolm (1978) found that seedlings of Sitka spruce in Scotland showed substantial weight gains over the winter period. However at treeline sites in continental areas, winter CO_2 assimilation is generally negative due mainly to loss of foliage (Tranquillini

1979, Mooney et al. 1966). In *Pinus aristata* at 3100 m Schulze et al. (1967) calculated that almost half the summer's CO_2 assimilation would be necessary to make up for winter losses.

Net photosynthesis of *Pinus cembra* was found to be influenced by soil temperatures (Tranquillini 1959) though Neilson et al. (1972) were not able to confirm this for Sitka spruce. The occurrence of frost can seriously affect photosynthesis the following day (Tranquillini 1979) and temperature conditions prior to measurement also affect measured rates of photosynthesis (Neilson et al. 1972).

The relationship between respiration and temperature in trees has received less attention than photosynthesis. Measurements of respiration made both on excised shoot and on trees in situ have demonstrated that respiration rates increase with increasing temperature. However, experimental evidence from alpine areas seems to indicate that respiration rates increase with increasing elevation (Tranquillini 1979, Benecke and Havranek 1980, Benecke and Nordmeyer 1982). This is generally regarded as signs of a metabolic acclimatisation to lower temperatures (Benecke and Nordmeyer 1982), though it is not immediately apparent why high respiration rates should confer any advantage to trees on high elevation sites, when this leads to an unfavourable CO_2 assimilation / respiration balance (Tranquillini 1979).

4.1.1.2 Tree growth patterns

Numerous studies have concentrated on the role of temperature in controlling the breaking of dormancy and the rate of shoot extension. Shoot growth commences only when the temperature exceeds a certain minimum value (Baldwin 1931, Kienholz 1941, Millar 1965, White 1974) or when a certain heat sum has been accumulated (Campbell and Sugano 1975, Perala 1985, Cannell and Smith 1983). In upland Britain Millar (1965) found that birch (*Betula pubescens*) grew in height only when the mean air and soil temperatures exceeded 5.1 - 5.6 °C. Cannell and Smith (1983) found that the date of budbreak in Sitka spruce was related to the combined effect of the accumulated temperature above 5 °C and the prior number of "chill days" (days with a mean temperature < 5 °C).

Shoot extension rates and total shoot growth are well correlated with growing season temperatures for a wide range of species with widely varying growth patterns (Hiley and Cunliffe 1922, Baldwin 1931, Millar 1965, Ford 1980). Shoot growth rates may also be affected by soil temperature though the relationship is not a close one. In the British uplands Millar (1965) found that the extension growth of birch was correlated with mean and maximum daily temperatures and was rather more loosely related to mean daily accumulated temperature above 5.6 °C and soil temperatures. Freezaillah (1974) showed that temperature was the most important of several environmental factors in determining the growth rate of potted Sitka spruce seedlings at different elevations. Tranquillini (1979) gives several examples of relationships between temperature and shoot growth near the alpine treeline. Kozlowski (1962) states that current season temperature affects the rate of shoot extension, while temperature during the previous season determines height growth potential by influencing the number of primordia laid down in the bud of the developing shoot and by influencing the amount of stored carbohydrates available.

The cessation of growth and the formation of terminal buds is largely under photoperiodic control (Wareing 1956), though temperature can have a modifying role (Pymar 1978, Cannell 1985).

Mikola (1962) used data from the Finnish national forest survey to show that the diameter growth of Norway spruce and Scots pine was well correlated with mean summer air temperatures, particularly the monthly means for July (Pine) and June (Spruce). The relationships were particularly close in areas near the arctic treeline. Diameter growth is more closely related to current season temperature because it is made more at the expense of carbohydrates produced during the current rather than those produced during the previous season.

Relationships between temperature and forest productivity have been demonstrated for both conifers and broadleaves on a a variety of site types. Farr and Harris (1979) showed that the site index of Sitka spruce was closely related to accumulated temperature above 5.1 °C over its entire latitudinal range. Stömberg and Tegnhammar (1985) found accumulated temperature to be significantly related to the productivity of beech in southern Sweden, though edaphic infuences were dominating. Hunter and Gibson (1984) found mean growing season temperatures to be useful predictor variables in a study of the growth of *Pinus radiata* in New Zealand. Blyth (1974a) found that the productivity of Sitka spruce in north-east Scotland was correlated with various short-term indices of temperature.

4.1.1.3 Temperature indices used in the study of tree growth.

Many different temperature indices have been used in the study of plant growth and productivity. One of the problems with the use of any meteorological data is that the choice of possible indices is very wide, including maximum, mean, minimum or accumulated values representative of an infinite variety of possible time periods ranging from fractions of seconds to tens of years. These time periods may run concurrently with the phenomenon under scrutiny, or be prior to it or both. The researcher is often required to make an arbitrary prior selection of indices, then if he has time, choose the best by assessing the degree of correlation between them and the phenomenon under scrutiny. The type of index used depends to a large degree upon the nature of the phenomenon being studied, as is summarised below:

1. Photosynthesis, assimilation, respiration: meristem, bud or leaf temperatures over short periods.
2. Shoot extension: maximum, mean, minimum or accumulated hourly or daily temperatures of both the air (traditionally) or plant organs.
3. Growth rates or increments of individual trees: mean or accumulated seasonal air or annual temperatures.
4. Forest production: long term mean or accumulated seasonal or annual air temperatures, often extrapolated from nearby meteorological stations; also growing season length.

Recent advances in recording techniques have allowed accurate monitoring of the temperatures of plant organs, particularly leaves, buds and meristems. Such techniques are particularly useful in ecological and physiological studies, allowing meteorological conditions to be more closely linked to physiological processes (Cleary and Waring 1969, Grace 1977). However for large scale studies such measurements are clearly impractical and the researcher has little choice other than to rely on standard measures of air temperature.

Studies of agricultural productivity in relation to air temperature in upland

Britain have shown that plant response to temperature can usefully, if simplistically, be divided into three distinct ranges (Hunter and Grant 1971, Bendelow and Hartnup 1980).

1. A lower threshold below which growth will not occur. This varies from species to species and to a limited extent within species according to origin and external factors such as photoperiod.
2. A temperature responsive range where temperature is the main factor governing growth and productivity.
3. A range where temperature is generally not limiting and other factors such as solar radiation balance and moisture supply become more important.

According to Hunter and Grant (1971), plants in upland areas are subject to temperature levels within the "temperature responsive range" for a large proportion of the growing season. This explains why productivity in upland areas is better correlated with temperature than it is in lowland areas where factors such as radiation balance and moisture supply are more important for a greater proportion of the growing season. Mikola (1962) reported closer correlations between temperature and forest growth in the north of Finland than in the south of the country and in Denmark and attributed this to similar reasons.

In meteorologically orientated studies of plant productivity an arbitrary temperature threshold is often used to define the growing season, 5.6 °C being the most common. Reduction in the length of the growing season is an important factor in crop productivity in the uplands (Manley 1945, Anderson and Fairbairn 1955, Smith 1984). This occurs with increasing elevation and latitude simply as the threshold temperature is reached at later dates in the spring and earlier dates in the autumn in cooler climates. Tranquillini (1979) reviewed the role of temperature and growing season length in determining tree growth near the alpine treeline and concluded that reduction in the time available for photosynthesis was of considerable significance.

The concept of a temperature threshold followed by a temperature range in which growth is related to temperature has resulted in the widespread use of accumulated temperature or heat sums as an index of temperature.

Accumulated temperature effectively integrates the effect of growing season length (time above threshold temperature) with growing season temperature (degrees above threshold temperature). It has been shown to be a useful index in a wide range of studies including forest growth and production (Mork 1960, Farr and Harris 1979, Sarvas 1965, 1966, Stömberg and Tegnhammar 1985), climatic classification (Birse and Dry 1970), shoot growth (eg. Millar 1965, Perala 1985) and the timing of phenological phenomena (Perala 1985).

A major problem facing researchers is the lack of meteorological data for remote areas. One way of overcoming this is by extrapolation of standard meteorological data from recording stations to intervening areas. This is standard practice in meteorological, geographical and certain plant-ecological studies. Extrapolated meteorological data have been used in a variety of studies of forest growth (eg. Mikola 1962, Hughes 1979, White 1982a, Hunter and Gibson 1984) including computer simulation models of growth (Running 1984). Data are most commonly extrapolated spatially but altitudinal extrapolation may also be used for factors such as temperature which show reasonably consistent relationships with elevation (Smith 1984).

Extrapolated data are subject to errors from a number of sources the most important of which are:

1. Errors arising from differences in site characteristics between meteorological stations and the intervening sites, particularly differences in aspect and slope.
2. Errors arising from the process of spatial extrapolation. Despite the use of computers which make spatial interpolation relatively simple, different solutions are arrived at according to, for example the number of data points which are included in the calculation for any particular interpolated point.
3. Errors arising from the application of standard lapse rates irrespective of location and time of the year.

The altitudinal extrapolation of temperature data generally entails the application of a standard lapse rate, the most commonly quoted of which for Great Britain is 0.6 °C per 100 m (Bendelow and Hartnup 1980, Birse and Dry

1970, Francis 1978, Smith 1984). Lapse rates in Britain and elsewhere have been reviewed by Grace (1977), Hughes (1979) and Smith (1984). Lapse rates vary with both location, time of the year and time of day. One of the obvious trends in Britain is for lapse rates to be highest in the spring (Manley 1945). Unfortunately insufficient data are available for regional or temporal variations to be taken account of in studies covering wide areas.

4.1.1.4 Temperature and the occurrence of treelines.

A correspondence between the occurrence of treelines and a summer temperature of about 10 °C has been known about for a long time and has become an ecological "rule of thumb" (Schröter 1912, Toumey 1947, Daubenmire 1954, Grace 1977). The mean summer tetratherm (ie. the mean temperature of the four warmest months), the mean temperature of the two warmest months and the mean July temperature have all been related to the position of the treeline in various parts of the world and for various tree species. Toumey (1947) reported that forest growth begins to become scrubby when the summer tetratherm is 10 °C (ie. the lower limit of the alpine ecotone), whereas most other authors have generally concentrated on the upper limit of the alpine forest ecotone and related this to the mean July temperature. Although the correlations are good on a geographical scale, considerable variation exists when the data are examined more closely (Schröter 1912, Grace 1977). For example Schröter (1912) reported that the limit for European larch and Mountain pine in the Bernina district of Switzerland corresponded with a mean July temperature of only 8 °C.

In Scotland Schröter (1912) calculated that the limit for birch on Ben Nevis (2110 feet) corresponded with a mean July temperature of 9.75 °C and stated that this corresponded well with the limit for birch in the Alps (9.67 - 10 °C). Spence (1960) noted a correspondence between mean June - July temperatures of 10 °C and the highest elevation occurrences of natural trees in mainland Scotland and in Shetland. Millar (1984) also reported a correspondence between the highest occurrence of planted trees and the mean temperature of the four warmest months in Scotland. The combined evidence from many part of the world points to the overriding importance of summer temperatures for the growth of trees at sites near the treeline (Grace 1977).

4.1.2 The effect of wind on tree growth.

Wind affects the growth rates, morphology and form of trees and other plants (Grace 1977). Reductions in growth rates as the result of wind have been noted in forest plantations (Booth 1976), in forest experiments (Fourt 1968, Thompson 1984) and in laboratory and wind tunnel tests (eg. Larson 1965, Rees and Grace 1980a, Dixon 1982). Until relatively recently, the effects of wind on tree growth have received remarkably little sustained research effort, even in temperate oceanic climates where wind is known to be a potent environmental factor.

4.1.2.1 The effect of windspeed on photosynthesis.

Reductions in plant growth rates due to the influence of wind are considered to result mainly from restriction of the rate of photosynthesis (Grace 1977, Tranquillini 1979). The two major mechanisms thought to be responsible for this are:

1. The lowering of leaf temperatures.
2. The induction of stomatal closure.

The temperatures of leaves exposed to radiation are normally higher than those of the surrounding air. This leaf to air temperature difference is generally greatest in large leaves, when adsorbed energy is high and when windspeeds are low (Warren-Wilson 1957, Jarvis et al. 1976, Grace 1977). Even in conifer needles considerable differences occur. For example Tranquillini (1968) found that mean monthly leaf temperatures of *Pinus cembra* growing at 2000 m at the alpine timberline exceeded mean air temperatures by about 2 °C. The corresponding mean maximum leaf temperatures exceeded mean maximum air temperatures by as much as 8 °C. Such differences obviously have fairly dramatic effects on the ability of plants to photosynthesise and grow, particularly on cool sites.

Wind acts to disturb the boundary layer adjacent to the leaf surface and so increase the rate of convectional heat loss (Grace and Dixon 1984). The decline in leaf to air temperature difference occurs rapidly with increasing windspeed. Leaf temperatures significantly higher than ambient air temperatures are generally only maintained at windspeeds lower than about 3 ms-1, the value of the difference being determined largely by the level of irradiance (Jarvis et al. 1976). As Grace (1977) points out, windspeeds of this order probably occur relatively frequently within tree canopies. Allen (1985) was able to demonstrate that different leaf temperature levels existed on windward and leeward sides of Sitka spruce crowns and was able to link this with differential growth rates on each side of the trees.

The closure of stomata due to wind may occur as the result of increased vapour pressure gradients which are established when the boundary layer is disturbed and/or as a result of impaired leaf water status (Dixon 1982, Grace 1977). The tendency for transpiration to increase when the boundary layer is disturbed by wind is offset to a certain degree by associated lowering of leaf surface temperature which tends to reduce transpiration rates (Grace 1977). Although considerable variation exists in the transpirational response of trees to increasing windspeed, an increase in transpiration is often observed for a period before increased stomatal resistance causes rates to decrease (Satoo 1962, Tranquillini 1979). In some genera (*Picea, Pinus, Sorbus, Rhododendron*), Tranquillini (1969) demonstrated a decrease in relative transpiration over a range of windspeeds from 0 to 20 m s^{-1}. Increasing stomatal resistance also causes photosynthesis to decrease (Grace 1977). Tranquillini (1969) noted a general decrease in photosynthesis with increasing windspeed for a range of species of tree and shrub and attributes this largely to impeded CO_2 uptake. Grace (1977) gives numerous examples of the same phenomenon for both crop and natural plants. However without simultaneous observations of stomatal resistance it is difficult to attribute the reduction in photosynthesis to specific causes.

4.1.2.2 The effect of wind-shaking on tree growth.

Reduced growth due to shaking have been noted in several plant species including trees and have been reviewed by Grace (1977). Neel and Harris (1971) demonstrated that the shaking of *Liquidambar* trunks for only 30 s daily was sufficient to reduce height growth by 70 - 80 per cent. Rees and Grace (1980a, 1980b) showed that shaking of *Pinus contorta* seedlings for 24 minutes daily reduced extension growth by 20% and a similar reduction was achieved by subjecting seedlings to windspeeds of 7 m s^{-1} in a wind tunnel. The mechanism responsible for such effects is unknown, though links between mechanical stimuli and increased respiration rates are possible (Grace 1977).

4.1.2.3 The effects of wind on the morphology and form of trees

Wind induces changes in the morphology and form of trees by both direct mechanical action and its effect on physiological processes. On high elevation sites such effects include abrasion of leaf/needle surfaces, loss of leaves and needles and the deformation of shoots, twigs and branches (Grace 1977, Allen 1985), and the induction of shrubby growth habits (Grace 1977). In plantations in Britain such symptoms are rather loosely described as exposure damage. Allen (1985) showed that loss of needles occurred due to the direct mechanical damage and that deformation of the branches and crowns was due to temperature-induced differential growth rates and the lignification of shoots displaced by wind action. High wind may also cause the loss of branches and shoots in trees. Hughes (1979) estimated that between 5 and 30 per cent of Sitka spruce trees lost their leading shoots annually on an exposed site near Aberdeen, Scotland. Wind also causes morphological changes to occur in the leaves of plants, these changes often being similar to those promoted by adaption to drought (Grace 1977).

Wind also affects the form of tree stems causing an increased ratio of radial to height growth (Jacobs 1954, Larson 1965) and eccentricity of the stem cross section (Skinnermoen 1969, Malcolm and Studholme1972). For example, Larson found that the stems of *Larix laricina* which were free sway, became more strongly tapered than the stems of trees which were stayed. The mechanisms responsible for initiating the cambial activity which leads to such a downward distribution of stem dry matter are unknown, though it seems likely that it they are responding to mechanical stresses.

4.2 Estimation of indices of temperature and wind-climate for the experimental sites.

4.2.1 Choice of indices.

The aim of including temperature and wind-climate in this study was to take the investigation one step nearer the physiological processes governing growth. Traditionally, studies of the relationships between tree growth and site variables in Britain have relied on geographical or topographic factors to describe the effects of climate (eg. Page 1967, Malcolm 1970). It was felt that the modest step nearer the growth processes of plants made by using carefully chosen extrapolated meteorological data rather than geographical and topographical factors may help to provide a clearer insight into the factors which influence the growth of trees on exposed sites. Some preliminary evidence which indicates that the geographical pattern of decreasing productivity with increasing elevation is similar to known patterns of windiness and temperature has been presented in Chapter 3. The following sections describe work which was carried out to establish quantitative relationships between yield class and data describing the temperature and wind-climate of the experimental sites.

The indices were chosen to fulfill the following criteria:

1. They had been shown to be related to tree growth or productivity in previous studies.
2. They were derived from sources which had a reasonable coverage in Scotland and northern England (eg. meteorological stations).
3. A reasonable basis existed, or could be established, for the extrapolation of values to give estimates for the individual sample plots.

Based on this the following indices of temperature and wind-climate were chosen:

1. Mean annual accumulated air temperature above 5.6 °C (day °C).
2. Mean air temperature for the period June - September (°C).
3. Tatter rate (cm^2 day^{-1}).

Mean annual accumulated temperature was chosen because relationships between forest productivity and temperature had been demonstrated using this index (see section 4.1.1). Mean air temperature of the four warmest months (June - September) was included because of its correlation with the limits to high forest growth (Toumey 1947). Tatter rate was included because tatter data represent the only widespread data available describing the wind-climate of remote upland areas and because of its frequent use in determining upper planting limits in Britain.

Estimates of the above indices *adjusted to sea-level* were also calculated and proved to be useful measures for describing geographical distribution of the temperature and wind-climate. For certain preliminary analyses the data were stratified by "windzone". Windzones comprise a rough regional classification of wind-climate frequently used for forest management purposes (see Miller 1985). A wind zone map is given in Appendix 10.

The following sections describe the methods used to make estimates of these indices for the individual sample plots.

4.2.2 Estimation of mean accumulated temperature.

Values of mean accumulated temperature above 5.6 °C were estimated for 71 meteorological stations in Scotland and northern England from data given by Birse and Dry (1970) and Bendelow and Hartnup (1980). They calculated values from meteorological records of monthly mean temperature and the standard deviation of the monthly mean temperatures using a procedure developed by Thom (1954) and Shellard (1959). As well as giving values of mean accumulated temperature for the elevation of the stations, they also calculated values for 100 m intervals above, and where appropriate below the level of the station using a standard lapse rate of 0.6 °C per 100 m .

In the present study a function was calculated for each station based on these data, which described the change in accumulated temperature with elevation. A very close fit was obtained using the quadratic function:

$$\text{Acc. Temperature} = a - b(\text{elevation}) + c(\text{elevation}^2)$$

$$r^2 = 98\text{–}100\%$$

The values of (a) above are the sea-level values of mean accumulated temperature for each station. These are given for all the meteorological stations in Appendix 4, and computer interpolated contours (isotherms) based on these values are shown in Figure 13. The values of (b) and (c) were similar for each station varying between 1.50 and 1.75 in the case of (b) and 0.0004 and 0.0006 in the case of (c). The values of (b) and (c) were plotted on maps but no geographical pattern was apparent. The values for each plot were therefore obtained by taking the appropriate sea-level values for each site from Figure 13 and applying the equation above with the values of (b) and (c) at average levels (−1.65 and 0.0005 respectively). The sea-level values for each site and the values for each plot are shown in Appendix 1.

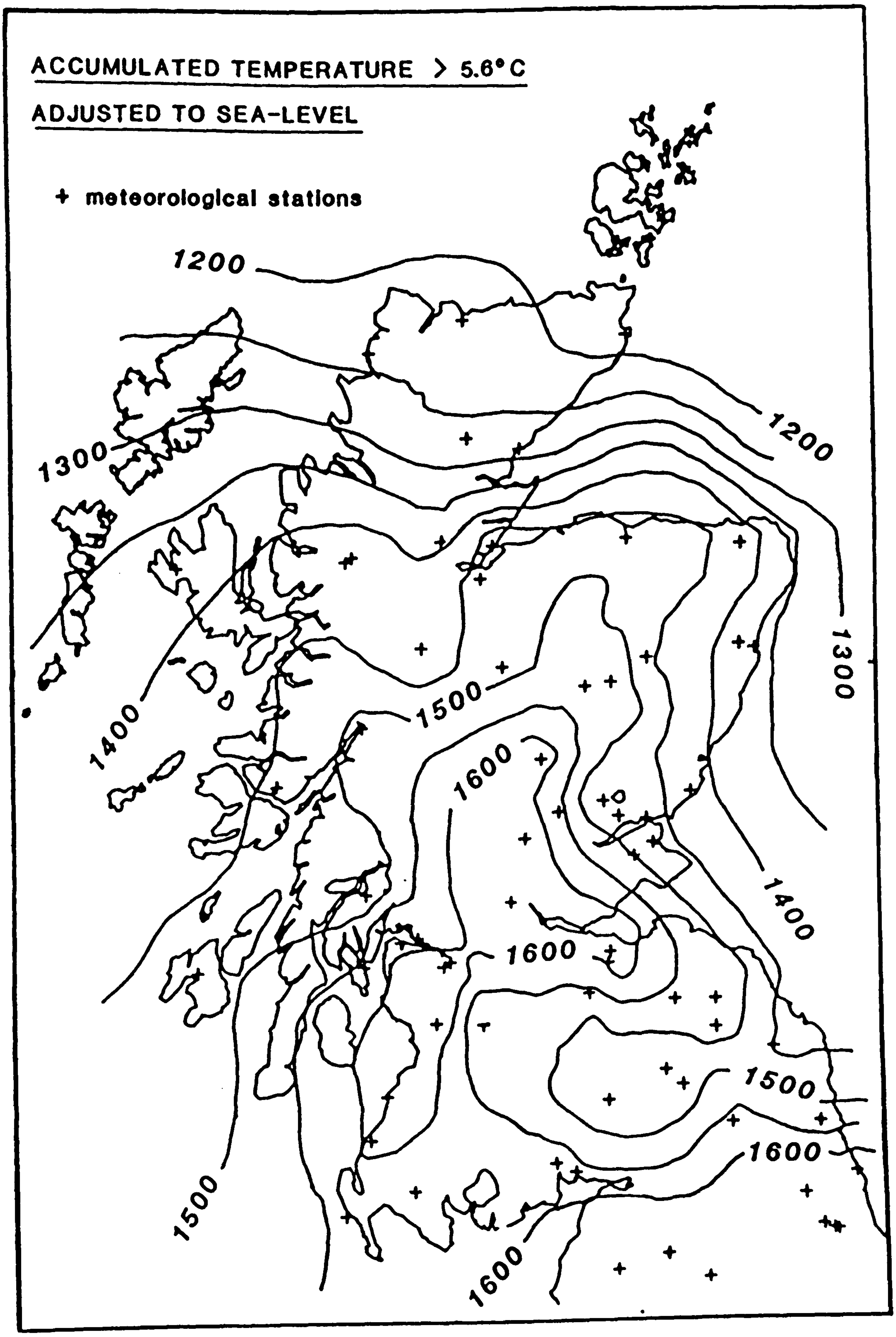


Figure 13. Sea-level values of mean annual accumulated temperature above 5.6°C

4.2.3 Estimation of mean summer temperature.

The values for the mean temperature of the four warmest months were estimated from meteorological data for 52 meteorological stations in Scotland and northern England (Meteorological Office 1976). For each station the values for mean monthly temperature for the appropriate months were taken and an average was obtained. These values were then adjusted to sea-level using a standard lapse rate of 0.6 ^{o}C per 100 m and the sea-level values were contour-mapped by computer (see Figure 14). The appropriate sea-level values for the fieldwork sites were then arrived at by interpolation using Figure 14. Finally, the values for the individual plots were calculated by extrapolating the sea-level value to the elevations of the plots using the standard lapse rate.

The appropriate sea-level values for each site and the extrapolated values for each plot are shown in Appendix 1.

4.2.4 Estimating tatter rate for the experimental sites.

In previous analyses of tatter flag data carried out by Forestry Commission staff only the effects of elevation and geographical location on tatter rate have been investigated (Miller et al. 1987). These analyses were carried out by sorting the data into groups from different geographical areas, each group showing a distinct relationship between tatter and elevation. These geographical groups were used along with maps of mean windspeeds to define the windzones (see Miller 1985). The windzones were used to give advice to forest managers on the risk of windthrow and on the upper limits to commercial planting.

Preliminary inspection of the data by the author showed that the relationships between tatter rate and geographical location and elevation were not close enough to allow prediction of tatter rate from these two variables alone. For example, stratification of the data according to windzone and calculation of regression lines for each windzone gave equations which only accounted for 28 - 62 per cent of the variation in tatter rate for the individual windzones.

Forestry Commission tatter flag records generally give the following details for each tatter flag:

1. Annual tatter rates for a number of years varying from one to three

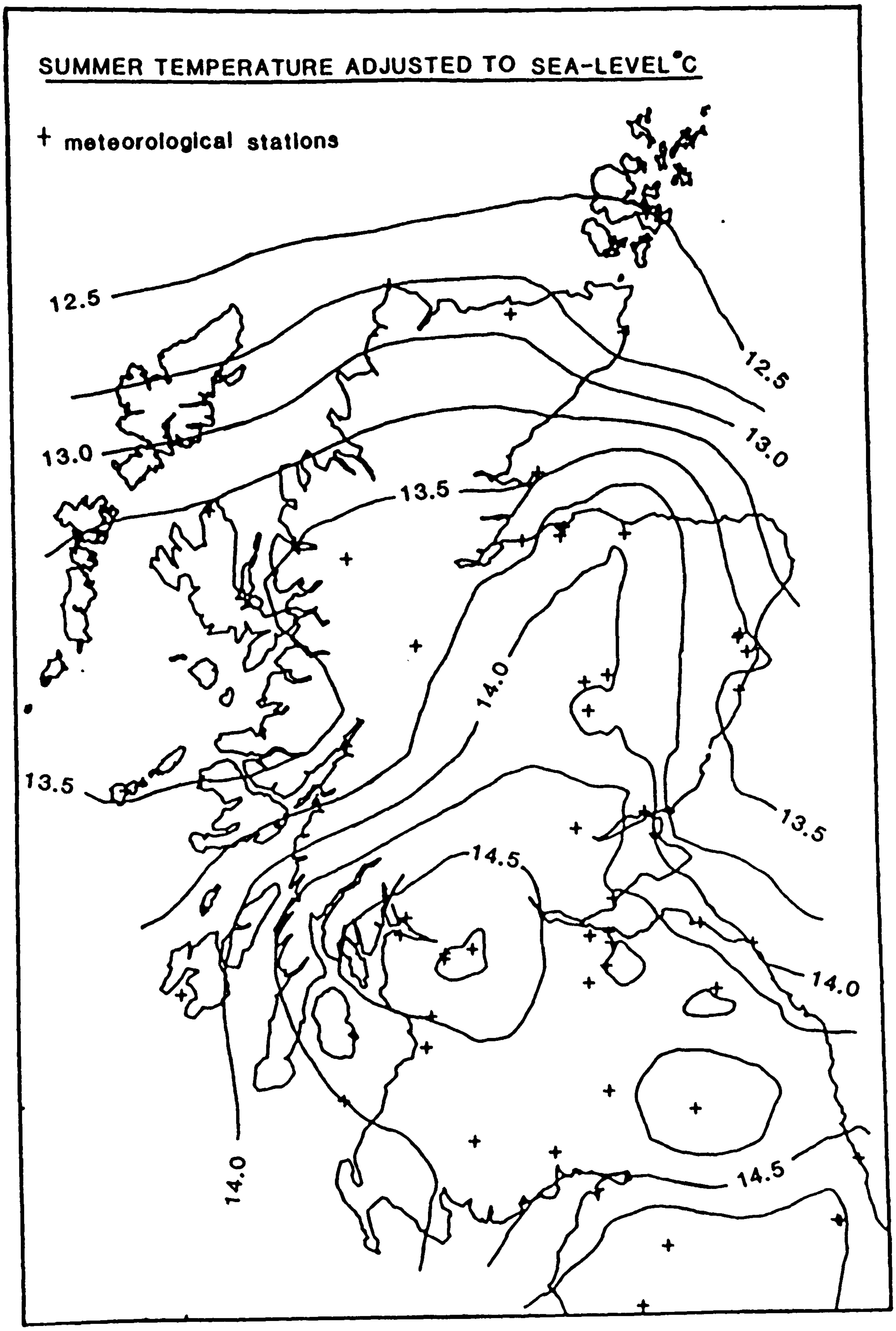


Figure 14. Sea-level values of mean summer (June-Sept.) temperature

and a three year mean where appropriate.

2. A six-figure grid reference.

3. Elevation.

4. Information on the relative exposure of the site, usually topex.

5. Aspect according to the eight main compass points.

A total of 1084 tatter flags had been exposed during the period 1957 to 1984. Of these, 564 flags on 109 sites had been exposed for the standard three year period and had reliable readings (ie. no reports of damage, no sheltering effects of nearby plantations). Value for topex and aspect, which were potentially useful as predictor variables were missing for about 120 of these flags. These missing values were obtained by site visits by the author and Forestry Commission staff or by reference to Ordnance Survey maps

In an attempt to find an improved method of predicting tatter rate from major site variables, topex and aspect were included in the analysis in addition to elevation, and dummy variables were used to estimate the effect of geographical location in the same way as described in section 3.2.3. A summary of the data is given in Table 5.

The analysis was carried out as an analysis of covariance with elevation and topex treated as continuous (metric) variables and aspect and geographical location treated as categorical (discrete) variables. The effects of both aspect and geographical location were estimated by using dummy variables. In the case of aspect ten categories were used, eight for the cardinal points of the compass, one for flat sites ("nil" aspect) and one for hilltops ("all" aspects). The reference category to which all other aspect classes were compared (see section 3.2.3) was hilltop sites. In the case of geographical location, 109 categories were used, one for each of the tatter flag sites. The most appropriate model was found to be:

$$\text{Tatter rate} = 0.0192(\text{elevation}) - 0.062(\text{topex}) + (\text{"aspect effect"}) + (\text{"site effect"}) \quad \ldots\ldots (8)$$

The effects of all the factors were significant ($P < 0.05$ or greater) and the model accounts for 76.7 per cent of the variability in tatter rate. Transformations of elevation and topex did not give significant increases in

Table 5. Description of tatter flag data.

VARIABLE	MEAN	MIN.	MAX.	S.D.
Elevation	348.4	20.0	725.0	136.1
Topex	26.3	0.0	123.0	3.14
Tatter rate	10.01	2.39	18.83	19.12

FREQUENCY DISTRIBUTION - TOPEX (FC CLASSIFICATION)

TOPEX	NO. OF FLAGS
0-10	100
11-30	266
31-60	156
61-100	41
100	1

FREQUENCY DISTRIBUTION - ASPECT CLASS

ASPECT	NO. OF FLAGS
N	42
NE	66
E	25
SE	68
S	75
SW	90
W	71
NW	82
NIL (level sites)	12
ALL (hilltop sites)	33

predictive power.

The values for the "site effects" and "aspect effects" are given in Appendix 5. They are also shown diagrammatically in Figures 15 and 16 and the patterns derived are described in the following two sections.

4.2.4.1 The effect of geographical location on tatter rate.

The values of "site effect" for the 109 tatter flag sites are given in Appendix 5, and a contour-interpolated map based on these values in shown in Figure 15. The values range from about 2 cm^2 day^{-1} in inland areas to about 12 cm^2 day^{-1} in western coastal areas. The values of "site effect" have been adjusted to give values of tatter rate when all other factors are set to zero (ie. rather paradoxically ; at sea-level, on a hilltop with a topex value of zero !) and can be regarded as tatter rate adjusted to sea-level. The geographical distribution of "sea-level tatter rate" is very similar to the pattern of wind zones (see Appendix 10), showing the highest values in northern and western coastal areas. The pattern shown would appear to give a satisfactory basis for the estimation of tatter rates from the model 8.

The pattern shown in Figure 15 differs from the pattern of windzones in two main ways. Firstly, the effects of geomorphic shelter (topex) and aspect have also been estimated in the analysis, so that variation from these sources is excluded from the estimation of the effect of geographical location. This is important, because if, for example, a site shows low tatter rates because of its topographic position (eg. east facing and/or high topex value) it would normally have been placed in a sheltered windzone irrespective of whether it was located in an otherwise more exposed region. Although areas of high geomorphic shelter tend to occur in "sheltered" windzones and areas of low geomorphic shelter in "exposed" windzones, this is not always the case. Such aberrant sites have occasionally caused difficulties when drawing up the windzone boundaries using traditional methods and in a few cases have led to the omission of data (Miller, K. pers. comm.). The covariance analysis carried out above effectively discriminates between low (or high) tatter rates caused by geographical location and low (or high) tatter rates caused by geomorphic shelter. This effect has led to a few subtle differences between Figure 15 and the pattern of windzones.

Secondly the contours have been arrived at mathematically, taking account

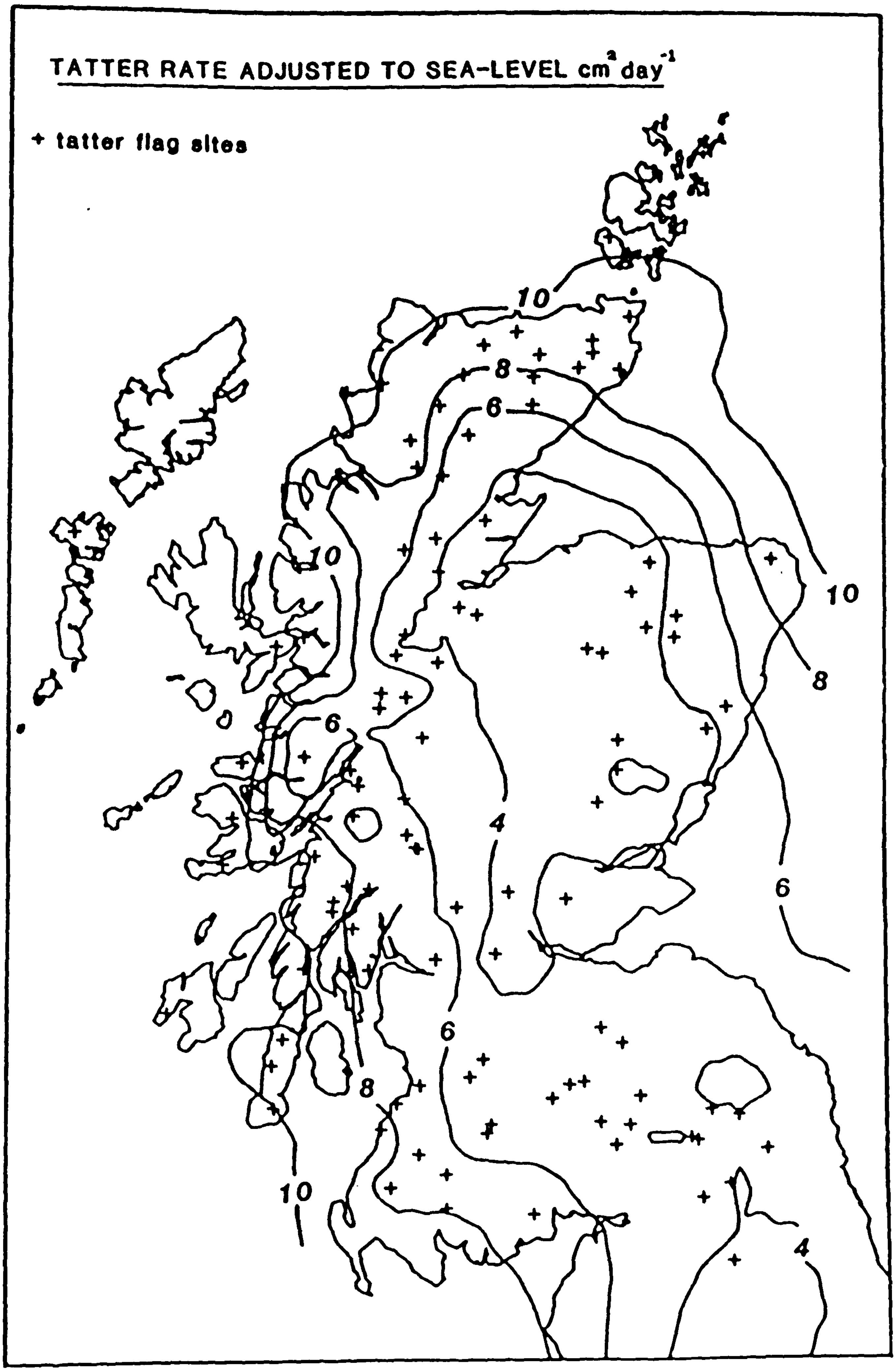


Figure 15. Site effect coefficients for the tatter analysis: sea-level values of tatter rate

of the nearest 24 data points when calculating the interpolated values, rather than being arrived at manually, with reference to usually only the nearest two or three values.

4.2.4.2 The effect of aspect on tatter rate.

The values of the "aspect effect" coefficients are given in Appendix 5, varying from 0.00 cm^2 day^{-1} (hilltop) to -2.33 cm^2 day^{-1} (east facing). Figure 16 shows the values of the "aspect effect" coefficients for the main compass points in terms of their deviations from the average value for all 8 compass points and compares this pattern with the solution provided by geometrical functions (see below). The pattern is clearly sinusoidal with east-facing aspects showing lower values of "aspect effect" than west facing ones (ie. east facing sites being more sheltered than west facing ones). The coefficient (ie "aspect effect") for west-facing sites is slightly aberrant with its value being below that expected from a sinusoidal pattern.

Investigation of the effect of aspect was also carried out using trignometric transformations. This was done by carrying out a regression analysis similar to equation 8 above but replacing the dummy variables for aspect with the terms sineθ and cosineθ, where θ is the angle of aspect measured clockwise from north. Level and hilltop sites were excluded from the data set. The model used was:

$$\text{Tatter rate} = a + b_1(\text{elevation}) - b_2(\text{topex}) + (\text{"site effects"}) + b_3\sin\theta + b_4\cos\theta \qquad \text{...... (9)}$$

The inclusion of both sine and cosine functions allows the angle of maximum amplitude (tatter rate) to take any value between 0 and 360 degrees. The values of b_3 and b_4 were -0.64 and -0.121. The resulting function is plotted in Figure 16 for comparison with the dummy variables. The angle of aspect associated with maximum exposure to was about 11 degrees south of west. This corresponds well with the direction of maximum windrun in Britain (Manley 1952) and confirms that tatter flags are sensitive to the aspect of the site.

4.2.4.3 Prediction of tatter rate for the sample plots.

Tatter rate was estimated for all the plots surveyed in this study using model 8. Values of "site effect" (ie. sea-level tatter rate) were interpolated from Figure 15 and the effect of aspect was estimated using the solutions

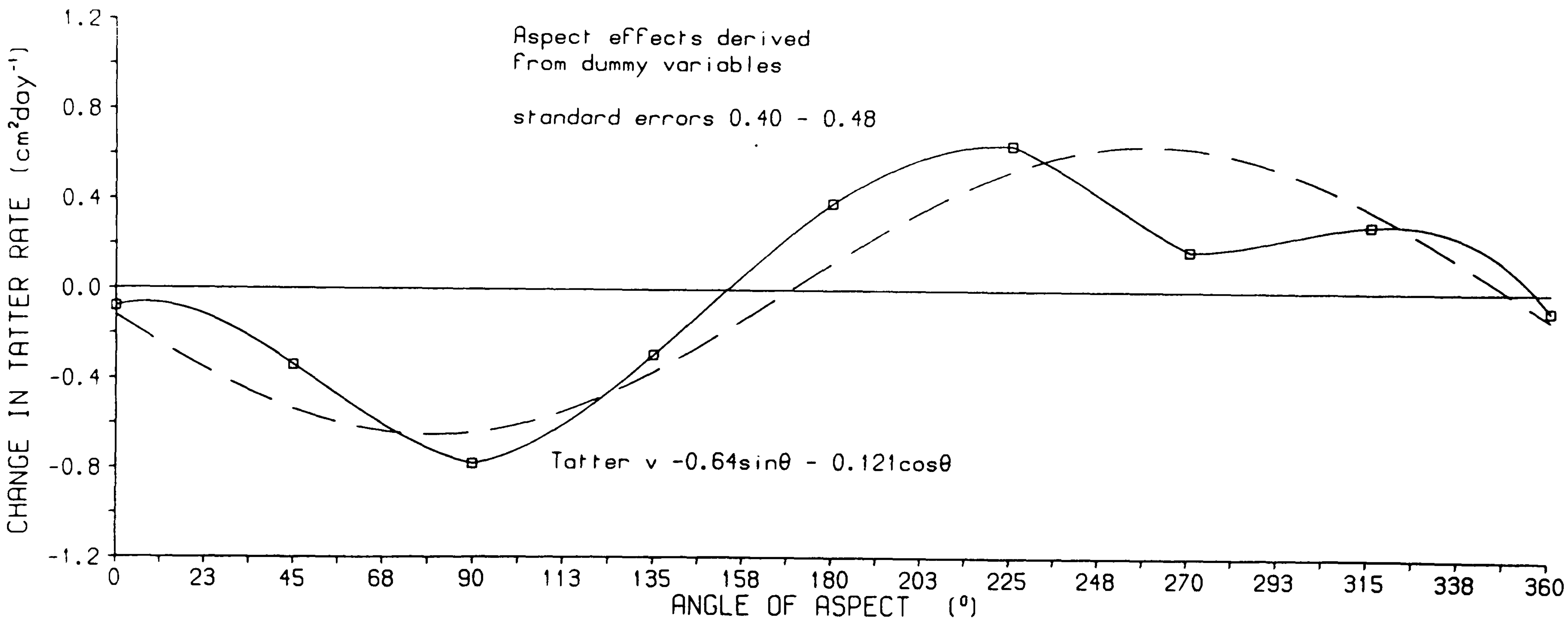


Figure 16. Effect of aspect on tatter rate

provided by the dummy variables. The confidence limits for prediction *applied to a specific site* were ±1.1 - 1.7 cm^2 day^{-1} for the regression model (mean values of y for specific combinations of x-values) and ±3.3 - 3.7 cm^2 day^{-1} for a single observation. The mean error of a single observation from the "true" value can be given by multiplying the standard error of the predicted Y-value by the ratio:

$(2/\pi)^2$ (Moran 1968)

This gives values of ±1.3 to 1.5 cm^2 day^{-1} for single new observations on a specified site. There is also an unquantifiable component of error associated with the interpolation of values of sea-level tatter rate from Figure 15. Such errors are associated with all meteorological data derived from maps. Despite these errors estimates of tatter rate made using model 8 probably represent the best data available for describing the windiness of upland forest sites in Britain.

4.2.5 Description of sample plot climatic data.

The main statistical characteristics of the climatic variables assessed are given in Table 6. For a full description of the data describing productivity, topographic and soil characteristics of the sites see section 5.1

The mean elevation of the plots was 366 m and ranged from 40 to 650 m. The mean value of estimated tatter rate was 8.5 cm^2 day^{-1} with a maximum of 14.4 cm^2 day^{-1}. The current prescriptions for planting limits are 12-14 cm^2 day^{-1}. The mean value summer temperature was 11.3 °C with a minimum value of 9.5 °C. A minimum value of 10 °C is usually associated with natural treelines. Accumulated temperature at sea-level varied from 1190 to 1610 day-degrees C with a mean level of 1505 day-degrees C. The values of accumulated temperature for the plots varied from 560 to 1374 with a mean of 977 day-degrees C. Topex varied from 1 - 130 with a mean value of 52.4.

Table 6. Mean, range and dispersions of climatic and topographic data for plots sampled.

	MAX.	MIN.	MEAN	MEDIAN	S.D.
GYC	27.0	6.2	13.96	14	3.97
ELEVATION	650	40	366.3	380	136.9
TATTER RATE	14.4	(0.00)	8.48	8.87	2.69
ACC. TEMPERATURE	1374	560	976.8	960.5	145.3
SUMMER TEMP.	12.8	9.5	11.28	11.21	0.67
TATTER (SEA-L)	11.7	3.0	6.2	6.0	1.94
ACC. TEMP. (S-L)	1610	1190	1505	1510	102.4
SUMMER TEMP. (S-L)	14.2	12.2	13.48	13.7	34.18
TOPEX	130.0	1.0	52.4	50	34.18

4.3 Effect of temperature and wind-climate on the productivity of Sitka spruce.

4.3.1 Comparison of site-to-site variation in yield class with variation in climatic variables.

A visual impression of the similarities between the geographical pattern of the variation in yield class and the temperature and wind-climate of the sites can be gained by comparing Figure 8 with Figures 13 (sea-level accumulated temperature), 14 (sea-level summer temperature) and 15 (sea-level tatter rate). The "site effects" shown in Figure 8 are independent of the effect of elevation and are therefore directly comparable with Figures 13, 14 and 15. The similarities between the patterns were analysed statisically by relating the values for "site effect" in model 3 to values of sea-level temperature and tatter rate for each site as derived from Figures 13, 14 and 15. These values are listed as part of the site data in Appendix 1 . The relationships were as follows:

Site effect = 13.1 − 1.93(tatter s.l.) r^2 = 73.5% ... (10)

Site effect = −40.1 + 0.0284(acc. temp. s.l.) r^2 = 57.3% ... (11)

Site effect = −90.2 + 6.87(summer temp. s.l.) r^2 = 61.8% ... (12)

The relationship between "site effect" and "sea-level tatter rate" was surprisingly close (r^2 73.5% - Figure 17), demonstrating that wind-climate is indeed a powerful factor in determining levels of productivity on upland sites. Sea-level temperature values were also strongly correlated with "site effect", but rather less closely than wind-climate (r^2 57.3% to 61.8% - Figure 18). The best two-variable model which included the effects of both wind and accumulated temperature was:

Site effect = −13.9 − 1.44(tatter s.l.) + 0.0165(acc. temp. s.l.)

r^2 87.8% .... (13)

Both wind-climate and temperature were significantly related to "site effect" ($P < 0.001$), demonstrating that both factors are important in determining the overall levels of productivity on upland sites. The relatively high r^2 values are partly due to the fact that this form of analysis deals exclusively with variation between sites and ignores within site variation.

The sea-level estimates of temperature and windiness at each site can be

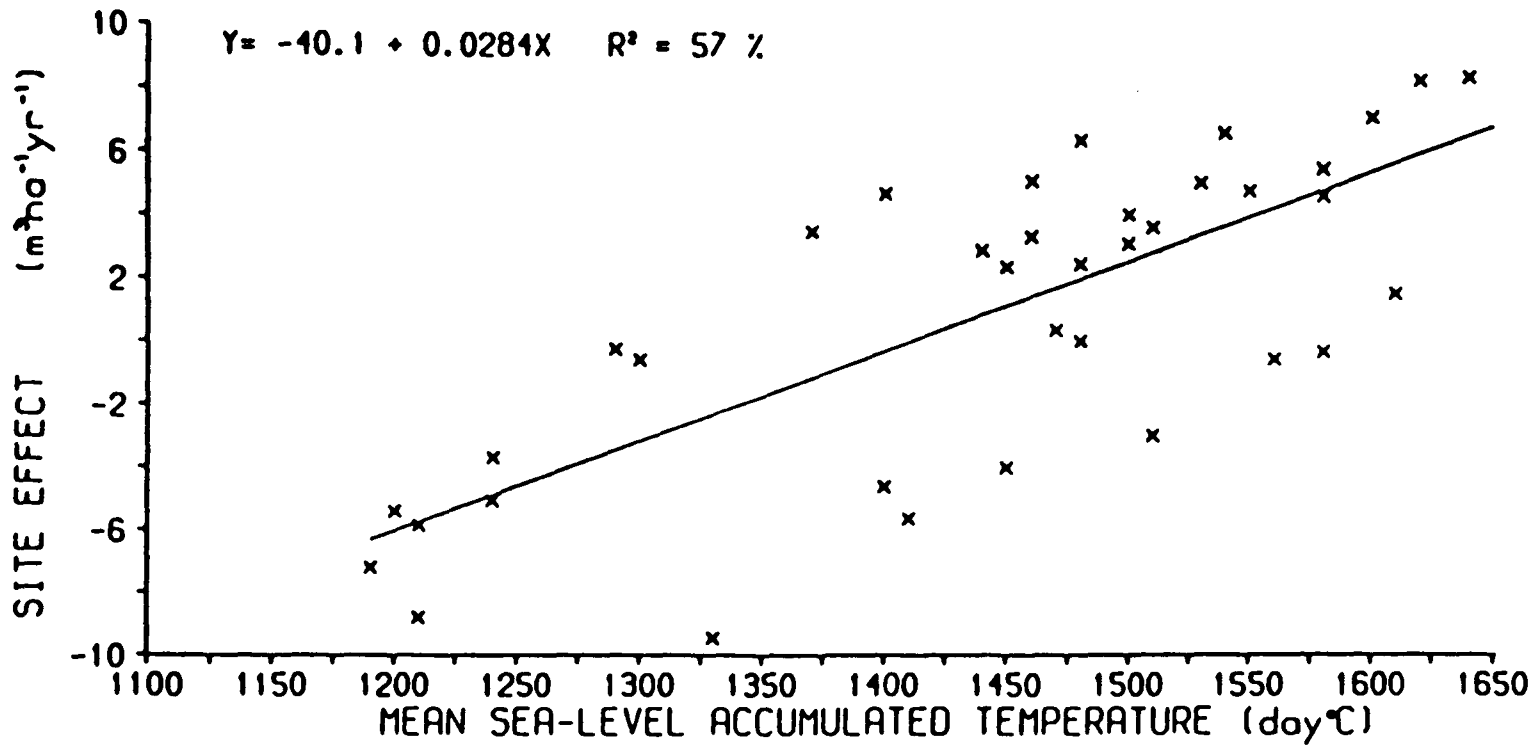


Figure 17. Relationship between site effect coefficients and sea-level accumulated temperature for the sites

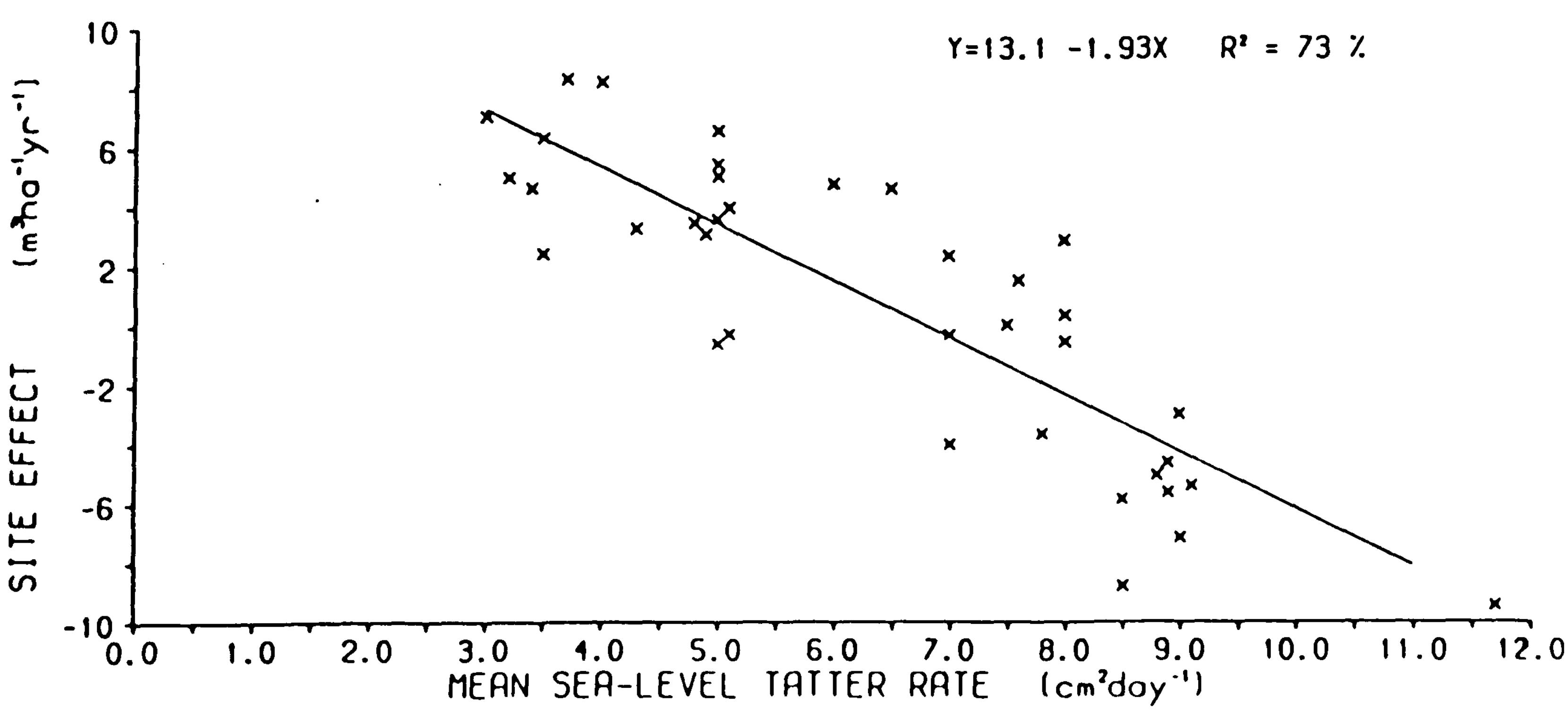


Figure 18. Relationship between site effect coefficients and sea-level tatter rate for the sites

related directly to the GYC at each site by calculating a regression between mean site GYC and mean site elevation, sea-level tatter and sea-level accumulated temperature. This essentially combines model 8 and model 13 above.

$$\text{Mean site GYC} = 14.2 - 0.316(\text{mean elevation}) - 1.09(\text{tatter s.l.}) + 0.0119(\text{acc. temp. s.l.}) \quad \ldots\ldots (14)$$

$r^2 = 77.7\%$

This model shows the separate effects of mean site elevation and the sea-level estimates of temperature and windiness on mean site GYC. Model 14 effectively states that an increase in elevation of 100 m is associated with a decrease in GYC of 3.2 $m^3\ ha^{-1}\ yr^{-1}$, an increase in tatter rate of 1 $cm^2\ day^{-1}$ *due to geographical location* is associated with a decrease in GYC of 1.09 $m^3\ ha^{-1}\ yr^{-1}$ and a decrease in accumulated temperature of 100 day °C *due to geographical location* is associated with a decrease in GYC of 1.19 $m^3\ ha^{-1}\ yr^{-1}$.

The 95 per cent confidence limits associated with this model were ±0.62 $m^3\ ha^{-1}\ yr^{-1}$ for the regression line and ±3.3 $m^3\ ha^{-1}\ yr^{-1}$ for a single site with mean values of the x-variables. The average error (estimated GYC - "true" GYC) for a single site can be estimated by multiplying the standard error of the predicted GYC values by the ratio:

$$\text{Average error} = (2/\pi)^{-2}\ \text{S.E.} \quad \text{(Moran 1968)}$$

For a site that had the mean values of the x-variables, the mean error is estimated to be ±1.3 $m^3\ ha^{-1}\ yr^{-1}$. This assumes that the sea-level meteorological variables are estimated without error. These results show that a model including elevation and sea-level estimates of tatter rate and accumulated temperature would probably form a satisfactory basis for predicting GYC from site factors.

4.3.2 Correlation analysis.

The relationships between GYC and the estimates of the temperature and wind-climate for the individual plots were investigated by correlation analysis. The correlation matrices are shown in Tables 7 and 8 . Values are given for two data sets:

1. The complete data set (188 plots).

2. Those plots having received standard modern silvicultural practice (drainage, ploughing, fertilising - 142 plots).

This separation was done in an attempt to remove silvicultural treatment or lack of it as a possible source of variation. It proved to be a useful subdivision of the data, particularly for subsequent regression analysis, with younger, cultivated crops generally showing higher yield classes and less variability than older, uncultivated ones.

Yield class was significantly correlated with the following factors: elevation, summer temperature, accumulated temperature, tatter rate, and cosine and sine of aspect. The strongest correlations were with the estimates of temperature and windiness, all of which showed higher r-values than did elevation. The correlations between GYC and cosine and sine aspect were both positive, indicating that the highest values of GYC are found where values of sine and cosine are both positive (0 - 90 ^{o}) as opposed to the sector 180 - 270 degrees where sine and cosine values are both negative. This shows that GYC values are highest on sheltered north and east-facing aspects rather than south and west-facing ones. The corresponding values for the relationships between aspect and tatter rate were both negative (and significant) reflecting the higher tatter values on south and west-facing slopes as expressed by the tatter model (model 8).

GYC was not significantly related to windzone or any of the *sea-level* values of temperature or tatter. This is because GYC was strongly correlated with elevation and the elevation of the plots varied systematically with respect to region. Plots in windy or cold regions tended to be at low elevations and those in sheltered regions tended to occur at high elevations. The result of this was that GYC values for the different regions were broadly similar.

GYC was significantly positively correlated with topex in the matrix for plots having received standard silvicultural treatment but not for the complete data set. Subsequent regression analysis showed that significant relationships with topex existed for the complete data set after the effects of other climatic factors had been accounted for. Topex was significantly correlated with the indices of sea-level temperature (positive), windiness (negative) for the data for plots having received standard silvicultural practice, illustrating the tendency for

Table 7. Correlation matrix of climatic and topographic data for the complete data set (188 plots).

			— EXTRAPOLATED VALUES —			— SEA LEVEL VALUES —					
	GYC	ELEV.	TATTER	ACC.TE	SUMM.TE	TATTER	ACC.TE	SUMM.TE	WINDZ.	TOPEX	COS
ELEVATION	-0.601										
EXTRAPOLATED VALUES											
TATTER	-0.587	0.382									
ACC. TEMP.	0.683	-0.829	-0.389								
SUMM. TEMP.	0.660	-0.851	-0.353	0.970							
SEA-LEVEL VALUES											
TATTER SL.	0.051	-0.671	0.094	0.512	0.547						
ACC. TEMP.	-0.065	0.570	0.099	-0.016	-0.090	-0.454					
SUMM. TEMP.	-0.123	0.587	0.182	-0.078	-0.074	-0.431	0.942				
TOPOGRAPHIC/CLIMATIC FACTORS											
WINDZONE	-0.137	0.717	-0.109	-0.546	-0.567	-0.855	0.498	0.488			
TOPEX	-0.018	0.153	-0.652	-0.096	-0.130	-0.023	0.146	0.092	0.235		
COS. ASPECT	0.263	-0.274	-0.159	0.195	0.252	0.127	-0.204	-0.132	-0.001	-0.065	
SIN. ASPECT	0.290	-0.022	-0.209	0.084	0.034	-0.157	0.075	0.010	0.089	-0.082	-0.005

Significance levels * 0.139, ** 0.188, *** 0.239.

Table 8. Correlation matrix of climatic and topographic data for 142 plots having received standard silviculture.

			—EXTRAPOLATED VALUES—			— SEA LEVEL VALUES —					
	GYC	ELEV.	TATTER	ACC.TE	SUMM.TE	TATTER	ACC.TE	SUMM.TE	WINDZ.	TOPEX	COS
ELEVATION	-0.641										
EXTRAPOLATED VALUES											
TATTER	-0.774	0.466									
ACC. TEMP	0.729	-0.832	-0.455								
SUMM. TEMP	0.670	-0.867	-0.446	0.956							
SEA-LEVEL VALUES											
TATTER	0.133	-0.695	0.151	0.585	0.655						
ACC. TEMP	-0.075	0.574	0.161	-0.028	-0.145	-0.401					
SUMM. TEMP	-0.204	0.604	0.214	-0.129	-0.127	-0.335	0.911				
TOPOGRAPHIC/CLIMATIC VALUES											
WINDZONE	-0.131	0.684	-0.097	-0.535	-0.579	-0.874	0.466	0.437			
TOPEX	0.240	0.154	-0.576	-0.032	0.001	-0.208	0.231	0.309	0.278		
COS. ASPECT	0.253	-0.300	-0.318	0.177	0.247	0.145	-0.274	-0.202	0.053	0.148	
SIN. ASPECT	0.286	-0.143	-0.208	0.186	0.083	-0.073	-0.002	-0.153	-0.046	-0.221	-0.045

Significance levels * 0.165, ** 0.216, *** 0.273.

higher levels of geomorphic shelter to occur in inland areas.

The estimates of temperature and windiness were generally significantly intercorrelated. This was true for the extrapolated values for the plots due mainly to the associated relationships with elevation and but also for the sea-level values, due to similarities in the geographical distribution of variation in wind and temperature.

4.3.3 Regression analysis.

Regression analysis was carried out to quantify the relationships between productivity and temperature and wind-climate and to try to identify the best models on which to base a system for predicting GYC from site factors. The regression equations and their corresponding r^2 values are shown in Table 9. Separate analysis was carried out for plots having received standard silvicultural treatment in an attempt to isolate the effects of site amelioration practices.

4.3.3.1 Effect of temperature on GYC.

Yield class was more closely correlated with estimates of temperature than with elevation. The r^2 values for the relationships between GYC and summer temperature and accumulated temperature for all 188 plots were 43.6 per cent and 46.6 per cent respectively, as opposed to 36.1 per cent in the case of elevation. The relationship between GYC and accumulated temperature for plots having received standard silvicultural treatment was closer, with an r^2 value of 53.1 per cent. GYC showed consistently closer relationships with accumulated temperature than summer temperature.

The increased r^2 levels obtained by using temperature values which are linear functions of elevation rather than elevation itself, are due to the similarities between the geographical distribution of variation in the GYC values and the geographical variation of the estimates of temperature described in section 4.3.1.

The relationships between GYC and accumulated temperature and summer temperature are shown in Figures 19 and 20. The different symbols used indicate the windzone that each plot lies in and as such give a crude estimate of the windiness each site. A tendency for plots in windier areas to show lower

Table 9. Relationships between GYC and some indices of climate and related factors (eg elevation).

EQUATIONS	R^2 VALUE%	MODEL
COMPLETE DATA		
GYC = 20.3 - 0.0174(elevation)	36.1	1
GYC = -30.4 + 3.93(summer temperature)	43.6	15
GYC = -4.26 + 0.0187(accumulated temperature)	46.6	16
GYC = 21.3 - 0.867(tatter rate)	34.5	17
GYC = -20.8 - 0.0234(elev.) + 3.21(sum. temp. s.l.)	44.2	18
GYC = -1.16 - 0.0242(elev.) + 0.0159(acc. temp. s.l.)	47.5	19
GYC = 33.1 - 0.0299(elev.) - 1.31(tatter s.l.)	58.8	20
GYC as function of elevation, stratified by windzone	59.3	21
GYC as function of acc. temp., stratified by windzone	62.4	22
GYC = 4.42 - 0.0560(tatter) + 0.0146(acc. temp.)	58.8	23
GYC = 14.0 - 0.0348(elev.) - 1.22(tatter s.l.) + 0.0135(acc. temp. s.l.)	66.8	24
GYC = 17.2 - 0.0354(elev.) - 1.27(tatter s.l.) + 0.0119(acc. temp. s.l.) + 0.0386(topex)	67.9	25
GYC = 15.5 - 0.0334(elev.) - 1.19(tatter s.l.) + 0.0112(acc. temp. s.l.) + 0.0112(topex) + 0.880(sin aspect) + 0.717(cos aspect)	72.5	26
PLOTS WITH STANDARD SILVICULTURE		
GYC = 21.4 - 0.0190(elevation)	41.0	27
GYC = -32.3 + 4.12(summer temperature)	44.8	28
GYC = -5.63 + 0.0205(accumulated temperature)	53.1	29
GYC = 25.8 - 1.25(tatter rate)	59.9	30
GYC = -15.1 - 0.0241(elev.) + 2.83(sum. temp. s.l.)	46.3	31
GYC = -2.31 - 0.0264(elev.) + 0.0175(acc. temp. s.l.)	53.8	32
GYC = 33.8 - 0.0315(elev.) - 1.29(tatter s.l.)	59.9	33
GYC as function of elevation, stratified by windzone	65.9	34
GYC as function of acc. temp., stratified by windzone	69.0	35
GYC = 9.53 - 0.902(tatter) + 0.0134(acc. temperature)	77.8	36
GYC = 10.2 - 0.0388(elev.) - 1.28(tatter s.l.) + 0.0175(acc. temp. s.l.)	72.6	37
GYC = 10.7 - 0.0381(elev.) - 1.19(tatter s.l.) + 0.0155(acc. temp. s.l.) + 0.0395(topex)	77.7	38
GYC = 12.3 - 0.0370(elev.) - 1.19(tatter s.l.) + 0.0144(acc. temp. s.l.) + 0.0364(topex) + 0.734(sin aspect) + 0.403(cos aspect)	80.8	39

Notes: 1. All factors significant at at least 5% level (except "cos aspect" in model 39).
2. Indices with suffix "s.l." are values adjusted to sea-level.

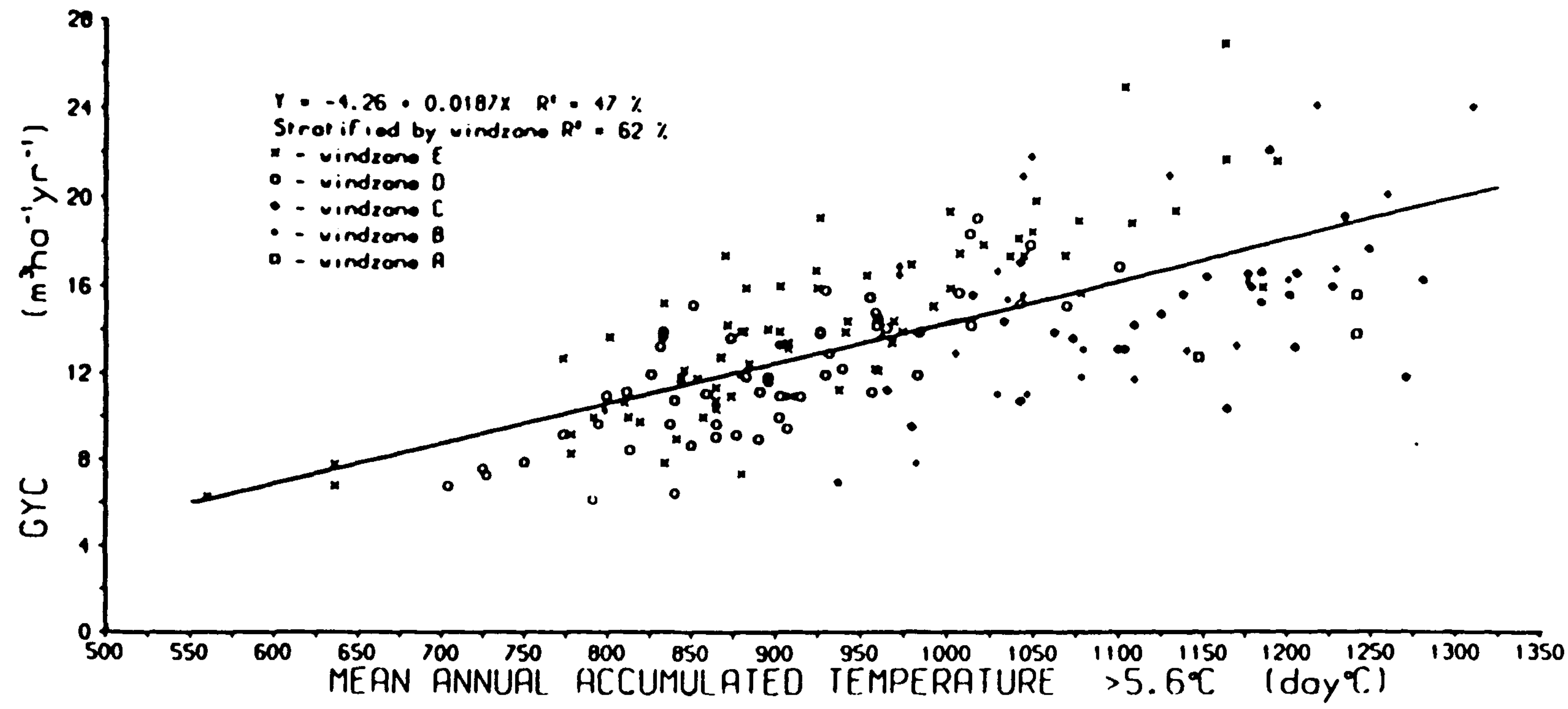


Figure 19. Relationship between productivity (GYC) and mean annual temperature > 5.6°C

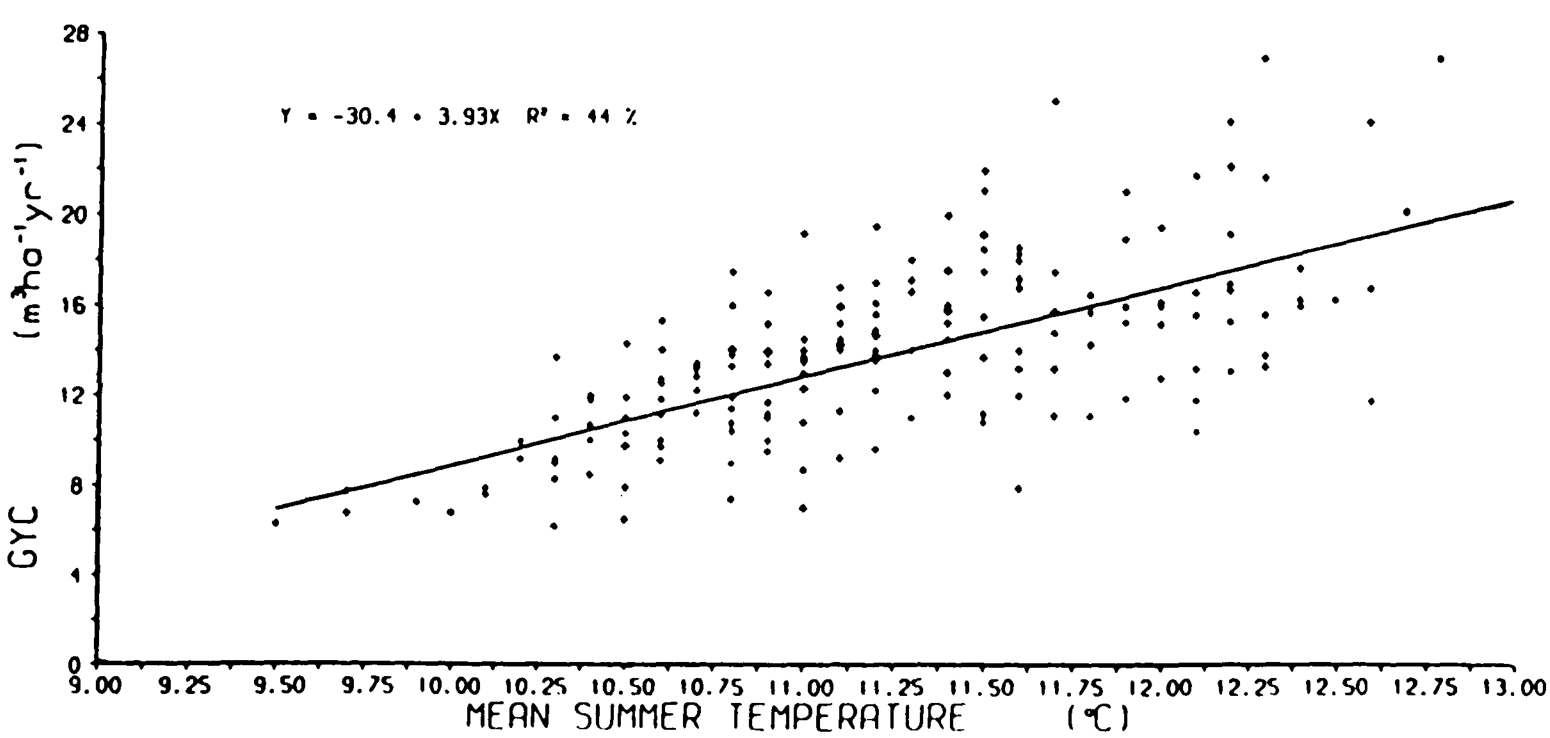


Figure 20. Relationship between productivity (GYC) and mean summer (June-Sept.) temperature

values of GYC for specific values of temperature is apparent. This is described in more detail in section 4.3.3.3.

4.3.3.2 Temperature, treelines and planting limits.

The elevation at which tree growth becomes scrubby is known to correspond roughly with the elevation at which the temperature of the four warmest months is 10 °C (see section 4.1.1.4). Figure 21 shows estimates of the elevations at which a value of 10 °C is reached in northern Britain. These vary from 350 m in the far north to 650 m in inland and southern areas. These values correspond reasonably well with estimates of the elevation of the treeline in the Cairngorms (see Pears 1967,1968). In some areas of western Scotland lower levels for the natural treeline are observed (Poore and MacVean 1957) than those indicated by Figure 21. This is presumably due to the influence of wind.

Figure 12 (section 3.3) shows estimates of the elevation of the commercial planting limit for Sitka spruce. This also shows values ranging between 300 m in the north (and west) and 650 m in inland and southern areas. Figure 20 shows that a temperature of the four warmest months of 10 °C corresponds approximately with GYC 8. A GYC value of 8 is generally considered to be the lowest level of productivity which is economically profitable in British forestry. This indicates a certain correspondence between the elevation at which forest growth becomes scrubby according to ecological theory and modern upper limits to afforestation in Britain. It should be emphasised that GYC 8 represents a higher level of productivity than one would expect to occur at the lower limit of the alpine ecotone in a natural forest. This means that rather than British Sitka spruce planting limits behaving as natural treelines, the level of productivity chosen as the acceptable minimum occurs rather fortuitously at approximately the same elevation (ie temperature level) as the upper limit of high forest growth in natural forests.

4.3.3.3 The influence of wind on GYC.

Windzone.

Windzone (see Appendix 10 for a wind zone map) proved to be a useful factor by which to stratify the data for preliminary investigation of the effect of wind on yield class. This is illustrated by Figure 22 in which General Yield Class

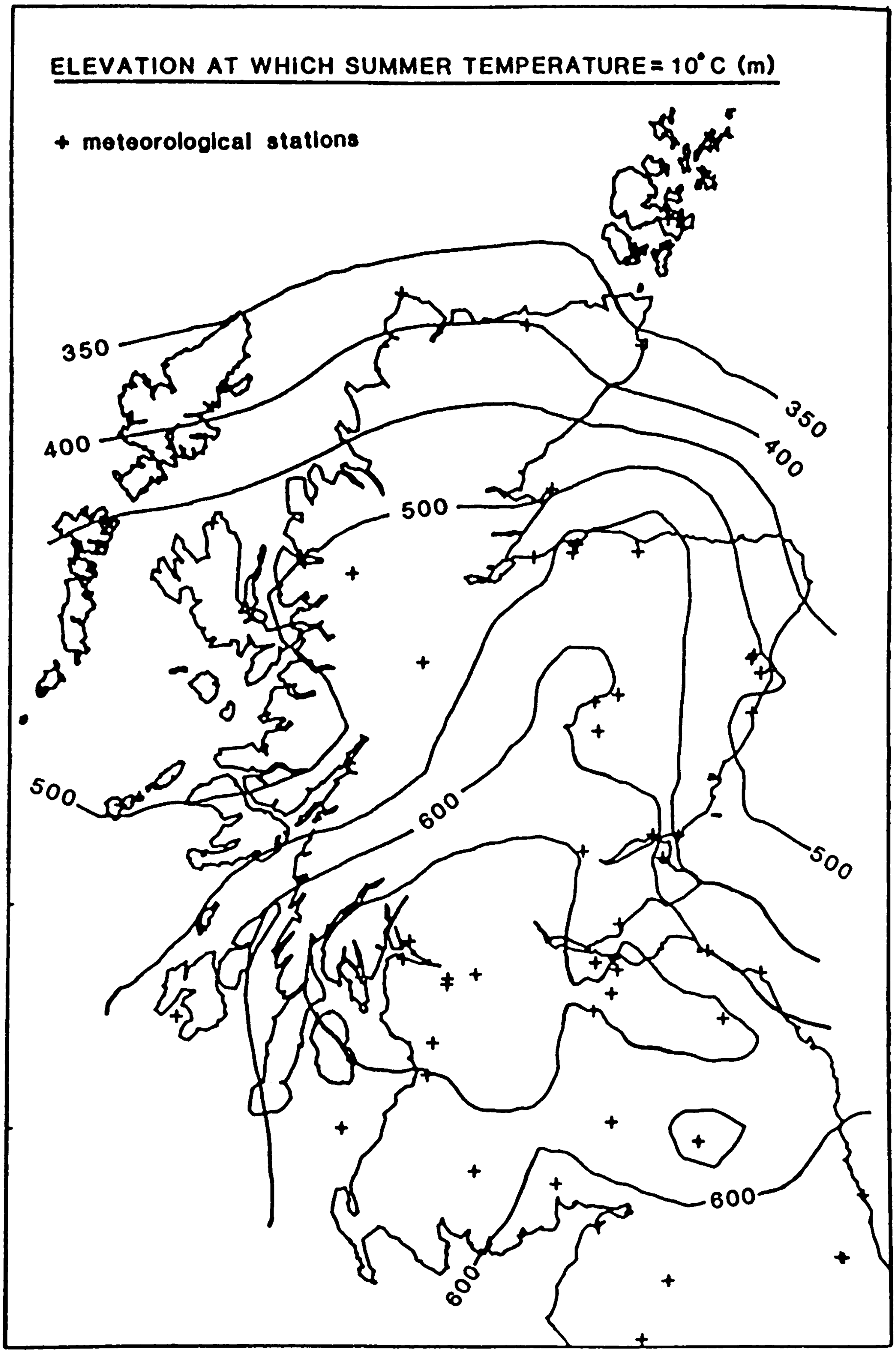


Figure 21. Elevation at which summer temperature is 10°C

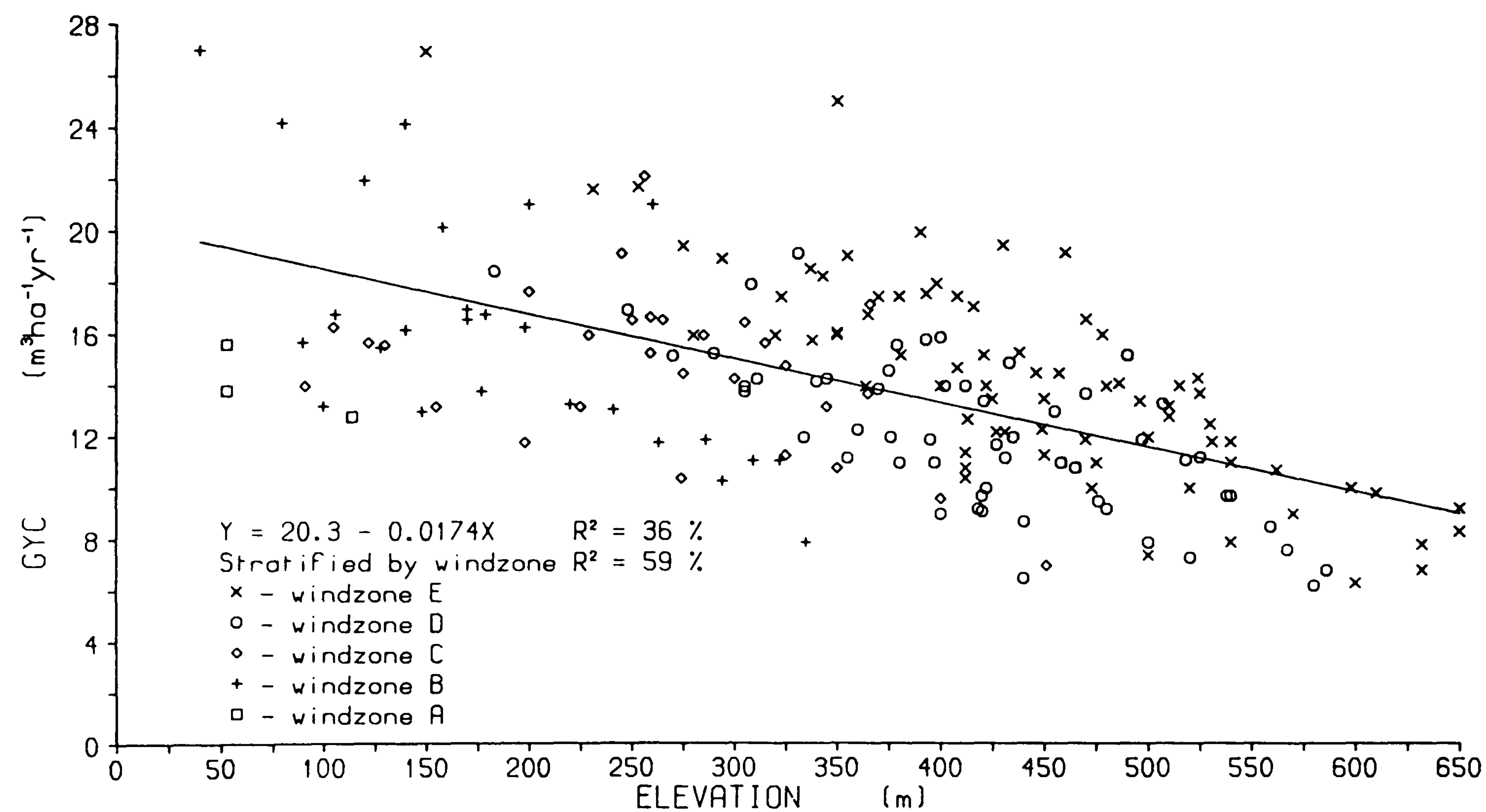


Figure 22. Relationship between productivity (GYC) and elevation, stratified by windzone

is plotted against elevation for the data for all the plots, with different symbols for the different windzones in which the plots occur. The data were stratified according to windzone and the following regression equations were obtained:

Windzone E GYC = 29.0 − 0.033(elevation) r^2 = 66.6%

Windzone D GYC = 22.7 − 0.025(elevation) r^2 = 59.8%

Windzone C GYC = 18.2 − 0.013(elevation) r^2 = 15.1%

Windzone B GYC = 23.8 − 0.041(elevation) r^2 = 46.7%

Windzone A GYC = 16.4 − 0.031(elevation) r^2 = 59.8%

Overall r^2 value for the complete data set = 59.3% ... (21)

Stratifying by windzone increased the r^2 value from 36.1 per cent (elevation only - see model 1) to 59.3 per cent (elevation and windzone). The overall value of 59.3 per cent, which is essentially an average value for the degree of correlation within windzones (weighted by number of plots per windzone), is very similar to the value obtained by Malcolm (1970) using only elevation as a regressor for the data from five sites (Bin, Glentress, Glengarry, Balquidder and Inverliever). Of these five sites, four were in windzone E and one (Inverliever) in windzone C. The relatively high degree of correlation between productivity and elevation recorded by Malcolm is probably due to the fact that the sites came from areas of similar windiness. It is apparent that such simple relationships do not apply for wider areas, and some sort of stratification according to geographical location is desirable, such as that provided by windzones. The relatively poor correlation for data from windzone C is probably due to the particularly diverse nature of the topography and soils at the two main forests represented (Arecleoch - rolling, deep peats; Sunart - steep and dissected, mineral soils)

A similar trend can be seen in Figure 19, in which GYC is plotted against mean accumulated temperature with different symbols for the different windzones. When these data were stratified according to windzone the following regression equations were obtained:

Windzone E GYC = −11.7 + 0.028(acc. temperature) r^2 = 69.3%

Windzone D GYC = −12.3 + 0.027(acc. temperature) r^2 = 61.3%

Windzone C GYC = −6.5 + 0.019(acc. temperature) r^2 = 32.5%

Windzone B GYC = −10.6 + 0.024(acc. temperature) r^2 = 40.2%

Windzone A GYC = $-10.2 + 0.020$(acc. temperature) $r^2 = 59.8\%$

Overall r^2 value for complete data set = 62.4% .... (22)

Accumulated temperature in combination with windzone is marginally more closely correlated with productivity than elevation and windzone ($r^2 = 59.3\%$).

Estimated tatter rate.

The relationship between yield class and estimated tatter rate for plots which had received standard silvicultural practice was the closest for any single regressor variable in this study (59 per cent). Models for both data sets which included both elevation and sea-level tatter rates also showed reasonably high r^2 values (58.8% and 59.9% - models 20, 33), with the inclusion of sea-level tatter rate adding over 20 per cent onto the r^2 value for the model containing only elevation. However, contrary to this a low degree of correlation (r^2 = 34.5%) was recorded for the relationship between GYC and tatter rate for the complete data set (model 17).

This was apparently due to the relatively poor relationship between GYC and estimated tatter on sites where the crops were old (40+ yrs). The inclusion of crop age in the relationship increased the r^2 value to above 60 per cent as shown below:

GYC = $30.6 - 1.37$(tatter) $- 0.19$(crop age) $r^2 = 62.4\%$ .... (17a)

The highly significant effect of age is probably mainly the result of the lack of cultivation acting as a source of variation. In addition, most of these older crops occur on sites in very dissected terrain, probably because such early plantations were undertaken mainly on sites with a high degree of geomorphic shelter. On such sheltered sites tatter flags are thought to operate less well than on windy sites (Miller pers. comm.).

Models 17 and 30 (see Table 9) show that GYC decreases by an average of 0.9 - 1.2 $m^3\ ha^{-1}\ yr^{-1}$ for an increase in tatter rate of 1 $cm^2\ day^{-1}$. The effect of geographical variation in sea-level tatter rate is treated separately from the effect of elevation in models 20 and 33. These show that (ignoring the effects of other factors) an increase in elevation of 100 m is associated with a decrease in GYC of about 3 $m^3\ ha^{-1}\ yr^{-1}$ and an increase in sea-level tatter rate of 1 $cm^2\ day^{-1}$ is associated with a decrease in GYC of about 1.3 $m^3\ ha^{-1}\ yr^{-1}$.

4.3.3.4 Combined effect of accumulated temperature and tatter rate on GYC.

General Yield Class was particularly well correlated with accumulated temperature and tatter rate combined (see Table 9), with r^2 values of 58.8 per cent (complete data - model 23) and 77.8 per cent (standard silvicultural practice - model 36). For models including sea-level values of temperature and windiness together with elevation the r^2 values were 66.8 per cent (complete data - model 24) and 72.6 per cent (standard silvicultural practice - model 37). All the effects in these models are significant ($P < 0.05$ or greater) and they are also logical, decreasing GYC being associated with increasing windiness and decreasing temperature.

These relationships illustrate that both the temperature regime and the wind climate of upland sites are important in determining tree growth rates. Thus "exposure"·can be conveniently described as the combined effect of low annual accumulated temperatures and unfavourable wind-climate and its effects on the growth rates of Sitka spruce can be quantified by the use of standard meteorological data (temperature) and tatter flag records (wind). However, it should be pointed out that "exposure" probably also involves the effects of other factors such as winter damage, which have not been included in this study.

Models 23, 24, 36 and 37 are probably good enough to form the bases for predictive models. These results seem to vindicate the use of tatter flags by the Forestry Commission, but it appears that for the purposes of predicting yield, their accuracy only begins to approach reasonable levels when account is also taken of the temperature regime of the sites.

The improvement in predictive power achieved by using temperature as well as tatter values reflects the fact that windy sites in coastal areas (Hebrides, Caithness, Kintyre) experience considerably higher temperatures than correspondingly windy sites in inland mountainous regions (Cairngorms). For example, in the Hebrides at 200 m the tatter rate is about 12 cm^2 day^{-1} and the accumulated temperature 1000 day-degrees whereas in the Cairngorms a tatter rate of 12 cm^2 day^{-1} occurs at about 650 m where the accumulated temperature is only about 550 day-degrees. Some recognition of this effect has been made by the Forestry Commission with regard to upper planting limits by prescribing upper values for tatter of 14 cm^2 day^{-1} for coastal areas and 12 cm^2 day^{-1} in inland areas (Reynard and Low 1984).

4.3.3.5 The relationship between actual tatter rates and GYC.

As mentioned in section 2.4, GYC was assessed on 39 sites where tatter flags had been flown prior to planting, so that measured values of tatter rate were available. Of these sites, 19 were located at Forestry Commission experimental sites, the remaining being located in standard plantations. The data for these plots are listed with the other plot data in Appendix 1. The data represent sites as diverse as 650 m altitude in the Cairngorm mountains to 200 m in the Outer Hebrides and near sea-level in Caithness. The relationships between GYC and actual tatter rate (and estimated accumulated temperature) were as follows:

<u>All plots (39)</u>

GYC = 20.9 - 0.775(Tatter) $\quad r^2$ = 32.7% ... (40)

GYC = 6.3 - 0.493(Tatter) + 0.0129(Acc. Temp.) $\quad r^2$ = 64.1% ... (41)

<u>F.C. Experiments (19)</u>

GYC = 22.9 - 1.07(Tatter) $\quad r^2$ = 53.1% ... (42)

GYC = 10.8 - 0.774(Tatter) + 0.0104(Acc. Temp.) $\quad r^2$ = 77.3% ... (43)

The correlations between GYC and tatter rate were lower than anticipated (33% and 53%) indicating that the relationship between tatter and GYC is not the same for the entire area (Scotland, northern England). However, when estimates of accumulated temperature were included considerably improved relationships were obtained (64% and 77%). This reflects the modifying effects of temperature as described in section 4.3.3.4 above.

4.3.3.6 The effect of geomorphic shelter on GYC.

Yield class is positively related to topex ($P < 0.001$) in models 25, 26, 38 and 39, demonstrating increasing levels of productivity with increasing geomorphic shelter. This contrasts with the effect of topex on tatter rates described in section 4.2.4, indicating that the effect of geomorphic shelter on GYC is probably mediated mainly through its effect on site windiness.

Models based on the complete data set show values of the change in GYC

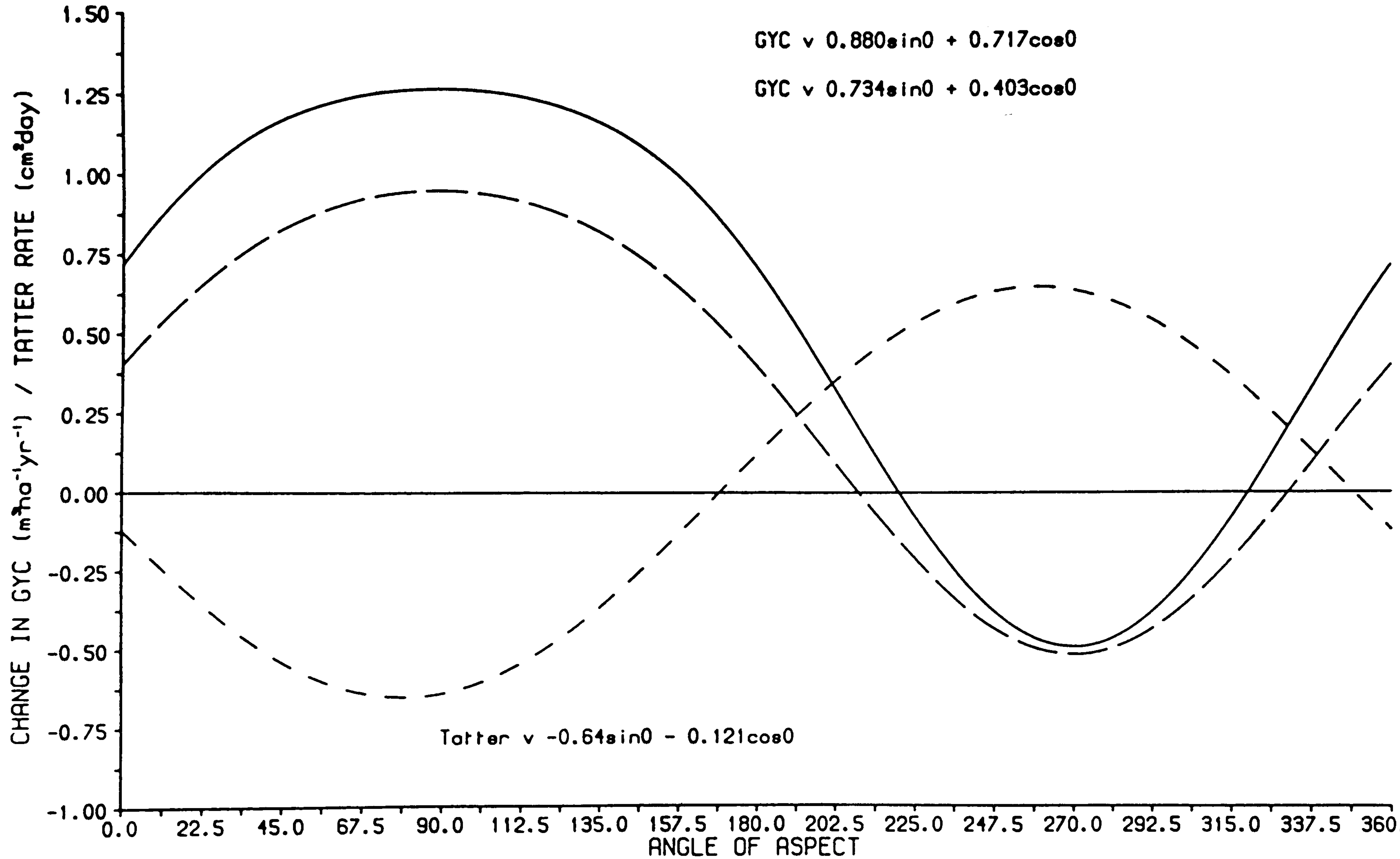


Figure 23. Relationship between productivity (GYC) and aspect

with topex of about 0.13 m^3 ha^{-1} yr^{-1} per 10 topex points. Models based on the data from plots having received standard silvicultural practice indicate that a change in topex of 10 points is associated with a change in GYC of about 0.4 m^3 ha^{-1} yr^{-1}. The difference in the two estimates arise from the tendency described in section 4.3.3.3 above for older slower growing crops to occur on sites with high geomorphic shelter. Several transformations of topex were tried for the complete data set but none resulted in a significantly improved relationship between GYC and topex. Subsequent analysis showed that the difference between the two data sets largely disappeared when the effect of crop age had been taken into account (see Chapter 5).

4.3.3.7 The effect of aspect on GYC.

Yield class was significantly related to aspect (sine/cosine transformation) in both data sets (models 26 and 39). The simultaneous use of sine and cosine transformations allows the angle of aspect associated maximum productivity to take any value. The sine/cosine functions are plotted in Figure 23 for the two data sets and the corresponding effect of aspect on tatter rate as calculated in section 4.2.4.2 is also shown. Note that data from 7 plots on level sites were excluded from models 26 and 39.

Productivity was highest in the quadrant north to east and lowest in the quadrant south to west. This pattern is clearly diametrically opposite to that of the effect of aspect on tatter rate, demonstrating that the effects of aspect on GYC are probably largely mediated through the effects of aspect on site windiness. No tendency for productivity to be greater on south-facing as opposed to north-facing slopes, consistent with a possible influence of solar radiation, was apparent. Further analysis of the effect of aspect on productivity is presented in section 5.3.3.1.

4.4 Conclusions.

1. The pattern of decreasing yield class with increasing elevation demonstrated in chapter 3 is closely related to variation in windiness and temperature as estimated by tatter rate and accumulated temperature.

2. Correlation and regression analysis of the data from the individual plots showed that the productivity of Sitka spruce on upland sites is related to the following climatic and topographic factors: elevation, derived sea-level values

of tatter rate and accumulated temperature, extrapolated values of tatter rate and accumulated temperature, topex and aspect (sine and cosine transformations). Models based on these factors accounted for 59-71 per cent of the variation in GYC for the complete data set and 73-79 per cent of the variation for data for plots having received standard silvicultural treatment. Productivity was greatest on sites with high levels of geomorphic shelter (topex) and on north to east facing aspects. Several models were calculated which could act as bases for the prediction of productivity from site variables.

3. For the purposes of predicting GYC on upland sites the term "exposure" may be defined as the combination of low annual accumulated temperatures and unfavourable wind-climate (high tatter rate) both of which may be quantified by spatial and altitudinal extrapolation of standard meteorological data (temperature) and tatter flag data (wind-climate). Estimated tatter rate and estimated accumulated temperature together accounted for 78 per cent of the variation in GYC for plots having received standard silvicultural practice.

4. Forestry Commission tatter flag data can be used to give estimates of wind-climate in the uplands where no other data exist. Tatter rate based on 562 flags was well correlated with the following major site factors: geographical location, elevation, topex (geomorphic shelter) and aspect. The geographical component of this variation showed a distribution very similar to known patterns of windiness including Forestry Commission windzones. Tatter rates were highest on sites with low levels of geomorphic shelter and on south to west facing aspects. Tatter rate was the single variable showing the highest degree of correlation with GYC for plots having received standard silvicultural treatment (59 per cent). However its predictive power was reduced in areas of high geomorphic shelter (low tatter rates).

5. The elevation of the natural treeline as predicted by the elevation at which mean summer temperatures are 10 °C varies between 300 m in northern Scotland to 650 m in central and southern areas. This is similar to the values predicted for planting limits for Sitka spruce based on a minimum acceptable GYC of 8.

CHAPTER 5

PREDICTING PRODUCTIVITY FROM SITE FACTORS.

In this chapter the relationships between productivity and the various site factors other than those included in chapters 3 and 4 are described in detail. Use is also made of regression techniques to derive regression equations for predicting General Yield Class of Sitka spruce from all the estimated site factors. Limited use is made of principal component analysis to illustrate some of the more complex intercorrelations between the factors. Some effects of elevation and exposure on tree form are also described.

5.1 Description of the data.

Frequency distributions for the site variables are shown in Figure 24 and some of their means and standard deviations are given in Table 10. Soil depth and rooting depth statistics for some of the more remote Forestry Commission experiments were not available from their files and statistics relating to these variables are based on 167 plots. For description of the climatic variables see section 4.2.5.

The mean yield class of the plots was 14.0 and ranged from 27.0 to 6.2. The mean value of 14.0 is about 2 m^3 ha^{-1} yr^{-1} higher than the national mean of 12 usually quoted for Sitka spruce. This is probably partly due to the generally favourable soil conditions on many of the sites (sloping valleyside sites) and the fact that a high proportion of the crops were relatively young and had had modern silvicultural treatment applied. Some surprisingly high values of GYC were recorded on low level sites in relatively exposed regions, these being probably due to high levels of geomorphic shelter (eg. Ratagan, Drumtochty).

Crop age varied from 10 years (only 7 observations in Forestry Commission high elevation experiments) to 53 years. The majority of plots were between 15-30 years old. The values for angle of slope varied from 0 ° to 36 ° with the majority of sites having slope values of 5-20 ° . Annual rainfall values spanned the range 1000 - 3600 mm yr^{-1} with a mean value of 1760 mm.

The most frequently recorded soil types were peaty gleys and surface water

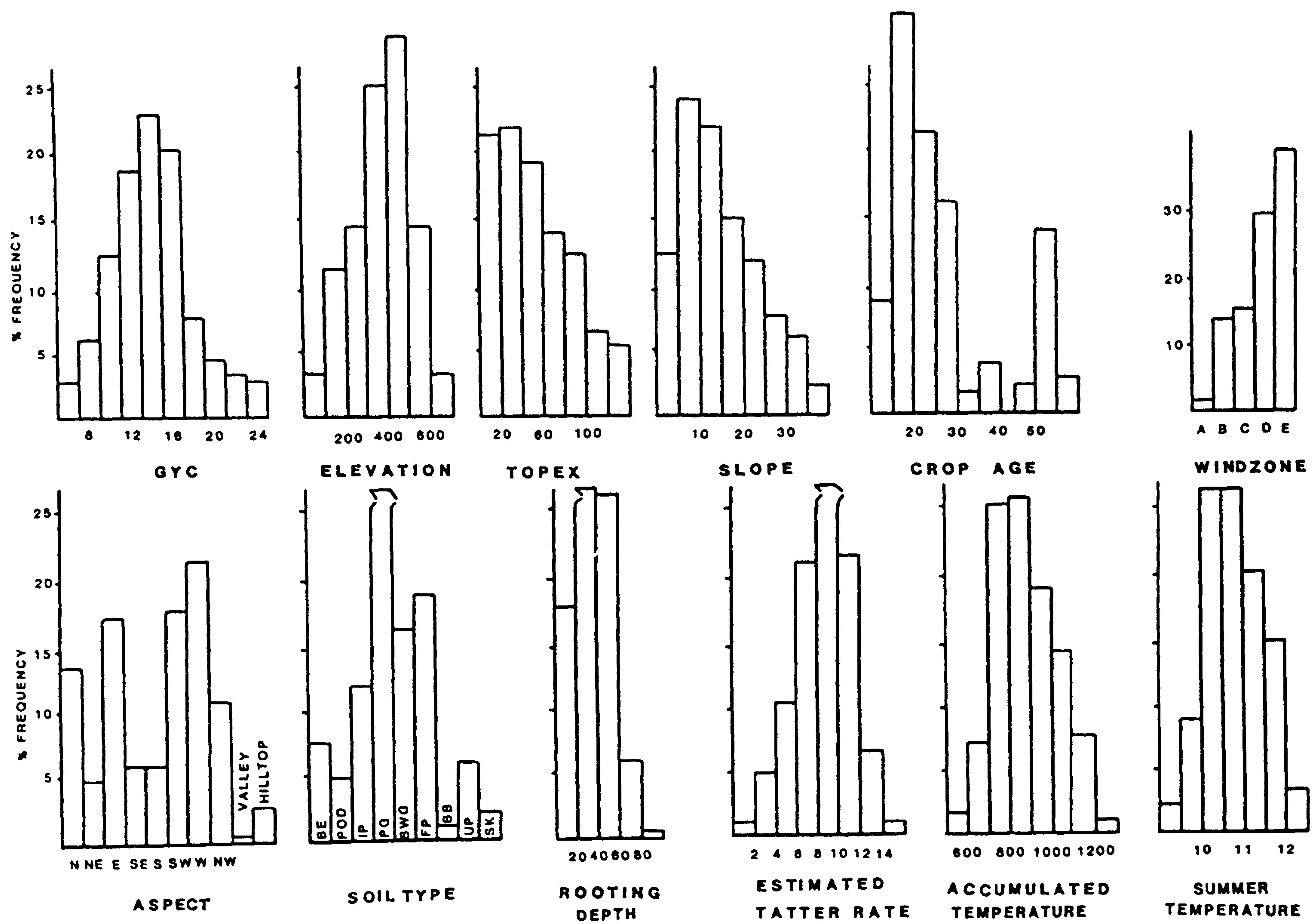


Figure 24. Frequency distribution for main site variables

Table 10. Ranges, means, medians and standard deviations of the variables assessed.

	MAX.	MIN.	MEAN	MEDIAN	S.D.
GYC	27.0	6.2	13.96	14	3.97
ELEVATION	650	40	366.3	380	136.9
WINDZONE	5	1	-	4	-
ASPECT	9	1	-	6	-
TOPEX	130	1	52.4	50	34.18
SLOPE	38	0	14.1	13	8.97
CROP AGE	57	10	26.5	22	13.2
TATTER RATE	14.4	(0.0)	8.48	8.87	2.69
ACC. TEMPERATURE	1374	560	976.8	960.5	145.3
SUMMER TEMP.	12.8	9.5	11.28	11.2	0.67
TATTER (SEA-L)	11.7	3.0	6.2	6.0	1.94
ACC. TEMP. (S-L)	1190	1610	1505	1510	102.4
SUMMER TEMP. (S-L)	14.2	12.2	13.48	13.7	34.18
RAINFALL	3500	900	1760	1760	602.6
PWD (class)	4	1	-	3	-
OCEANITY (class)	3	1	-	2	-
SOIL DEPTH	100	40.0	78.12	80.0	18.99
ROOTING DEPTH	99.0	10.0	43.30	44.0	16.19

gleys followed by flushed peats. Rooting depth varied from 10 cm to over 1 m with the lowest values being recorded on peat soils. Soil depths for soils other than deep peats varied from 40 cm to the maximum excavated depth of 100 cm.

5.2 Correlation analysis.

The correlation matrix for the data from all the plots is shown in Table 11. A large proportion of the correlations were statistically significant. This is partly due to the prior choice of factors, many of which had been shown to be related to GYC in previous studies, and partly due to the large numbers of sample plots. Two mains groups of highly significant correlations are apparent:

1. Intercorrelations between GYC, elevation, accumulated temperature, summer temperature and tatter rate. These have been described in detail in chapter 4.
2. Intercorrelations between crop age, topex, slope and rainfall.

The latter set of correlations is the result of a tendency for sites with old crops to occur in areas of highly dissected terrain and relatively high rainfall (western and central highlands), whilst younger crops occur more frequently on sites with less geomorphic shelter and with rather lower rainfall (Caithness, Borders, East Scotland). This probably reflects the pattern of early afforestation of the uplands in which plantations were generally established only where a relatively high degree of shelter existed. Latterly afforestation has taken place in more exposed terrain.

Yield class was negatively correlated with rainfall. This is probably due to the fact that high rainfall values are generally associated with higher elevation sites (note the significant positive correlation between rainfall and elevation), which in turn are characterised by low yield class values. Yield class and angle of slope were significantly negatively correlated, probably because increasing slope angle is associated with increasing elevation. Both slope and topex were correlated with windzone illustrating the tendency for "coastal" windzones to be associated with low geomorphic shelter and slope values and "inland" windzones to be associated with more dissected terrain.

Yield class was correlated with rooting depth though the coefficient (0.15) was very low and was significant only at the 5 per cent level. There was no

Table 11. Correlation matrix for the complete data set.

	GYC	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Elevation	-0.601													
2. Tatt.(S-L)	0.051	-0.671												
3. Tatter	-0.587	0.382	0.094											
4. Acc.t.(S-L)	-0.065	0.570	-0.454	0.099										
5. Acc.temp	0.683	-0.829	0.512	-0.389	-0.016									
6. Summ.temp	0.660	-0.851	0.547	-0.353	-0.090	0.970								
7. Rainfall	-0.190	0.190	0.179	-0.257	0.244	-0.080	-0.074							
8. Topex	-0.018	0.153	-0.023	-0.652	0.146	-0.096	-0.130	0.759						
9. Slope	-0.244	0.329	-0.089	-0.367	0.099	-0.331	-0.376	0.637	0.810					
10. Sin aspect	0.290	-0.022	-0.157	-0.209	0.075	0.084	0.034	-0.194	-0.082	-0.127				
11. Cos aspect	0.263	-0.274	0.127	-0.159	-0.204	0.195	0.252	-0.058	-0.065	-0.087	-0.005			
12. Root.dep.	0.154	0.172	-0.338	-0.363	0.071	-0.153	-0.201	0.113	0.337	0.378	0.276	-0.026		
13. Soil.dep.	0.066	-0.062	0.046	-0.013	0.180	0.186	0.181	-0.012	-0.033	-0.029	0.169	-0.099	0.192	
14. Age	-0.123	0.080	0.003	-0.545	0.022	-0.095	-0.122	0.572	0.773	0.581	0.075	-0.199	0.220	-0.015

Significance levels * 0.139, ** 0.188, *** 0.239.

relationship between total soil depth and GYC.

5.3 Multiple regression analysis.

Multiple regression analysis was used to investigate the effects of the site factors either singly or in combination and to derive predictive models. Dummy variables were used to allow the effects of categorical (discrete) variables to be estimated as well as those of metric ones (Nie et al. 1975). A description of the use of dummy variables is given in Appendix 9.

One possible problem with multiple regression analysis is in selecting the best multiple regression from the large number of equations that it is possible to calculate. For example, it is possible to calculate over 1000 different regression equations from a data set containing 10 predictor variables. If transformations are included the number become practically limitless. Difficulties arise in attempting to sort through the calculated regressions in a logical fashion whilst at the same time incorporating prior knowledge about the relationships which the investigator may have.

One method of arriving at the "best" multiple regression is to use stepwise regression techniques. In the following analyses a stepwise procedure was used which selects in sequence those variables with the highest F-statistics, rejecting those whose values fall below 4 at any point in the calculation process. This means that the effects of all the variables are significant ($P <$ 0.05 or greater). Other methods (algorithms) are available which would not necessarily lead to the same end result. One disadvantage of stepwise techniques is that many models will be calculated and in the process, combinations of variables may be chosen which are well correlated with the dependent variable but appear illogical to the investigator (Mead and Curnow 1983). Also sets of dummy variables cannot be treated in the same way as single variables and therefore cannot be included. Stepwise techniques are powerful exploratory tools but the results should not be regarded as unique correct solutions but rather as bases from which to direct further analysis.

5.3.1 Strategy for multiple regression analysis.

Multiple regression analysis was carried out with the aim of deriving models which accounted for the greatest proportion of the variation in GYC, in which all the effects of the predictor variables were significant ($P <$ 0.05 or greater), were logical and gave a reasonably complete picture of the properties of a forest site. The strategy adopted was as follows:

1. To use stepwise regression techniques to find the suitable models which describe:
   a. the change in GYC with increasing elevation and the geographical pattern of this relationship, making use of the relationships between GYC and climatic factors demonstrated in chapter 4.
   b. the effect of the other quantitative site variables.
2. To investigate the effects of the qualitative (categorical) variables by introducing them into the models chosen in 1. above by means of dummy variables.

At stage (1) above, the variables included were: elevation, extrapolated tatter and temperature values for the plots and sea-level values of estimated tatter and accumulated temperature, geomorphic shelter (topex), slope, crop age and rainfall. Stepwise regression analysis was also carried out excluding the extrapolated values of tatter rate and accumulated temperature. This was done to provide an alternative form of model in which the effects of prior assumptions made during the extrapolation process (lapse rates, the effects of topex and aspect on tatter rate etc.) were largely excluded. Analysis of the effects of rooting depth, and total soil depth were included in a separate analysis.

At stage (2) above, the variables introduced were: soil type, aspect, PWD, and oceanicity.

As is often the case with survey data, the X-variables listed above are not independent of each other. The existence of correlations between the X-variables does not invalidate the use of multiple regression analysis but it does mean that problems are encountered in disentangling the effects of the individual variables. Mead and Curnow (1983) state that multiple regression techniques:

"are at their most powerful and useful when there are correlations among the X-variables" and that it is the "only technique that takes proper account of these correlations and dependencies".

5.3.2 Stepwise regression analysis.

Table 12 shows the results of stepwise regression analysis for both the complete data set and the data for the plots having received standard silvicultural treatment. The first two variables chosen were estimated tatter rate and estimated mean accumulated temperature, which together accounted for 59 per cent and 78 per cent of the variation in GYC for the two data sets (as described in chapter 4). This is a particularly efficient basic model because a large proportion of the variation in GYC is account for by relatively few predictor variables. It should be noted that although estimated tatter rate and accumulated temperature appear as single variables, they are in fact extrapolated from several other factors (see section 4.2.4). This means that both of these variables have errors attached to them due to the extrapolation process, the magnitude of which are largely unknown.

The next variable included was crop age with coefficients indicating that an increase in crop age of 10 years is associated with an average decrease in GYC of 0.9 - 1.2 m^3 ha^{-1} yr^{-1}. This is presumably a reflection of the effects of improved silvicultural practice on crop productivity over the age range of the crops surveyed (planted 1935-1970). Estimated tatter rate, accumulated temperature and crop age together accounted for 72 per cent and 79 per cent of the variation in GYC, which is fairly high for a three variable model.

The fourth step in the case of the complete data set included the effect of angle of slope, this appearing as the fifth step for plots having received modern silvicultural treatment. GYC decreased by 0.6 - 0.9 m^3 ha^{-1} yr^{-1} for every 10 degrees increase in slope angle. The fourth step in the case of plots having received standard silvicultural treatment included a further negative effect of increasing site windiness (sea-level tatter value). This is rather illogical considering that this effect is already included in the estimates of tatter rate and this variable was excluded in further analyses. The four variable models (44; and 45 recalculated excluding sea-level tatter rate) accounted for 74 per cent and 80 per cent of the variation in GYC for the two data sets.

Stepwise regression analysis was also carried out excluding the extrapolated values of tatter rate and accumulated temperature for the plots (Table 13).

The first variable chosen was elevation, followed by sea-level tatter rate

Table 12. Stepwise regressions including extrapolated values of tatter and accumulated temperature.

COMPLETE DATA SET

Model 44

STEP	1	2	3	4
CONSTANT	-4.262	4.419	16.767	20.669
Acc.temp.	0.0187	0.0146	0.0100	0.0076
T-RATIO	12.75	10.46	7.90	5.58
Tatter		-0.560	-1.036	-1.139
T-RATIO		-7.41	-12.80	-13.86
Age			-0.142	-0.120
T-RATIO			-9.27	-7.63
Slope				-0.090
T-RATIO				-3.94
S	2.91	2.56	2.12	2.04
R^2	46.63	58.84	71.95	74.15

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Model 45

STEP	1	2	3	4	5
CONSTANT	25.775	9.526	13.083	10.683	14.109
Tatter	-1.252	-0.902	-1.028	-0.906	-1.014
T-RATIO	-14.46	-12.42	-12.37	-9.74	-9.70
Acc.temp.		0.0134	0.0127	0.0162	0.0140
T-RATIO		10.58	10.06	8.99	6.81
Age			-0.084	-0.091	-0.088
T-RATIO			-2.89	-3.18	-3.11
Tatt.s.l.				-0.33	-0.27
T-RATIO				-2.70	-2.18
Slope					-0.059
T-RATIO					-2.17
S	2.64	1.97	1.92	1.88	1.86
R^2	59.88	77.77	79.04	80.10	80.76

Table 13. Stepwise regressions excluding extrapolated values of tatter and accumulated temperature.

COMPLETE DATA SET

Model 46

STEP	1	2	3	4	5
CONSTANT	20.34	33.07	13.98	14.41	17.16
Elevation	-0.0174	-0.0299	-0.0348	-0.0354	-0.0354
T-RATIO	-10.25	-16.21	-19.19	-19.61	-20.62
Tatt.s.l		-1.31	-1.22	-1.26	-1.27
T-RATIO		-10.09	-10.36	-10.72	-11.41
Temp.s.l			0.0135	0.0131	0.0119
T-RATIO			6.69	6.54	6.21
Topex				0.0123	0.0386
T-RATIO				2.48	5.16
Age					-0.086
T-RATIO					-4.53
S	3.18	2.56	2.30	2.27	2.16
R^2	36.10	58.78	66.84	67.92	71.17

PLOTS WITH STANDARD SILVICULTURE

Model 47

STEP	1	2	3	4	5
CONSTANT	21.36	33.82	10.21	10.70	12.02
Elevation	-0.0190	-0.0315	-0.0388	-0.0381	-0.0394
T-RATIO	-9.87	-14.21	-18.88	-20.41	-20.53
Tatt.s.l		-1.29	-1.28	-1.19	-1.28
T-RATIO		-8.10	-9.73	-9.83	-10.22
Temp.s.l			0.0175	0.0155	0.0161
T-RATIO			7.99	7.69	8.04
Topex				0.0395	0.0478
T-RATIO				5.57	6.11
Age					-0.072
T-RATIO					-2.35
S	3.20	2.65	2.20	1.99	1.96
R^2	41.03	59.93	72.60	77.66	78.53

and sea-level accumulated temperature values. This gives a simple basis for a model, with GYC declining at about 3.6 - 3.9 $m^3\ ha^{-1}\ yr^{-1}$ per 100 m increase in elevation, by 1.27 $m^3\ ha^{-1}\ yr^{-1}$ for every 1 $cm^2\ day^{-1}$ increase in sea-level tatter rate and by 1.2 -1.6 $m^3\ ha^{-1}\ yr^{-1}$ for every 100 day-degree decrease in sea-level accumulated temperature.

The fourth step included the effect of geomorphic shelter (topex). An increase in topex of 10 points is associated with an increase in GYC of about 0.4 - 0.5 $m^3\ ha^{-1}\ yr^{-1}$. The fifth step included the effect of crop age, with GYC decreasing by about 0.9 - 1.1 $m^3\ ha^{-1}\ yr^{-1}$ for every 10 yrs increase in age. All the effects described above are apparently logical and between them account for a reasonably high proportion of the variation in GYC (71 - 79%).

Models 44 and 46 (complete data set) and 45 and 47 (plots with standard silviculture) were selected for inclusion in further analysis.

5.3.2.1 The effect of soil depth and rooting depth.

Stepwise regression analysis was carried out for the data set of 167 plots for which complete records of soil and rooting depth were available. The techniques and variables included were identical to those in section 5.3.2 above but also included rooting depth and total soil depth. The only significant relationship demonstrated by stepwise regression analysis was between GYC and rooting depth when analysis was as follows:

$$GYC = 17.3 - 0.035(\text{elevation}) - 1.15(\text{tatter s.l.}) + 0.011(\text{acc. temp. s.l.})$$
$$+ 0.029(\text{rooting depth}) - 0.094(\text{crop age}) + 0.034(\text{topex}) \quad \ldots (48)$$

The coefficient for rooting depth indicates that an increase in rooting depth of 10 cm is associated on average with an increase in GYC of 0.3 $m^3\ ha^{-1}\ yr^{-1}$. It should be noted that rooting depth could not easily be used as a predictor for GYC for the assessment of bare land for planting. Total soil depth was not significantly correlated with productivity.

5.3.3 Effect of categorical variables.

The following factors were treated as categorical variables: aspect, soil type, PWD (class), Oceanicity (class). These were introduced into the best regression models produced by stepwise regression analysis ie. models 44-47. The variables were included in the regression models by estimating their effects using dummy variables. A description of the use of dummy variables is given in Appendix 9. Testing the significance of the effect of including a set of dummy variables can be done by summing the sums of squares for each of the dummy variables, dividing by degrees of freedom for the dummy variables (n-1) and comparing this with the root mean square error of the model, as for a standard f-test.

The equations derived are shown in Table 14 and 15 and the coefficients for the categorical variables are illustrated in Figures 25 and 26. Tables 14 and 15 give the deviation of coefficients for each category from the average values of the coefficients for all the categories for each equation. This means that instead of comparing each category (soil type, aspect etc.) with its appropriate reference category, it is compared with the average of all categories. Thus the coefficients for the categories given in Tables 14 and 15 give estimates of the deviation from average in $m^3\ ha^{-1}\ yr^{-1}$ associated with each category. For example according to the analysis carried out using model 49, the effect of an east-facing aspect is to increase GYC by 1.49 $m^3\ ha^{-1}\ yr^{-1}$ whereas that of a south-west aspect is to reduce GYC by 1.00 $m^3\ ha^{-1}\ yr^{-1}$. Similarly according to the analysis carried out using model 51, the effect of a brown earth is to increase GYC by 2.18 $m^3\ ha^{-1}\ yr^{-1}$ whereas an unflushed peat reduces growth by 2.03 $m^3\ ha^{-1}\ yr^{-1}$. Figures 25 and 26 show the same effects in graphical form for the complete data set.

5.3.3.1 Aspect

The effect of aspect was first estimated by assigning one dummy variable to each aspect category (eight compass points, valley bottom sites and hilltop sites - see model 49). The coefficients for the compass points varied from about + 1.5 on east and north-east facing sites to -1.0 on south-west and north-west facing sites. The values for the different aspects are plotted in Figure 25 which shows that the pattern is roughly sinusoidal, with the highest values generally occurring on east facing sites and the lowest on west facing sites. South-east facing sites deviate from this pattern by showing low values of productivity (-0.73). Valley bottom sites showed a coefficient of +1.63 and hilltop sites -1.80.

A similar pattern is also shown by models 54 and 57 in which the effects of the different soil types are also included. However in these models the number

Table 14a. Coefficients and R^2 values for models including categorical variables aspect and soil type; complete data set.

VARIABLE	COEFFICIENT		
Model No	49	50	51
CONSTANT	19.61	19.30	19.06
ELEVATION	-0.0341	-0.0334	-0.339
TATTER	-	-	-
TATTER S.L.	-1.25	-1.17	-1.12
ACC. TEMP.	-	-	-
ACC. TEMP. S.L.	0.0100	0.0098	0.0101
TOPEX	0.0469	0.0433	0.0278
SLOPE	-	-	-
SIN ASPECT	-	1.160	-
COS ASPECT	-	0.291	-
CROP AGE	-0.108	-0.102	-0.129
ASPECT CATEGORY			
N	0.17	-	-
NE	1.44	-	-
E	1.49	-	-
SE	-0.73	-	-
S	0.66	-	-
SW	-1.00	-	-
W	-0.81	-	-
NW	-1.03	-	-
LEVEL - VALLEY	1.63	1.49	-
LEVEL - HILL	-1.80	-1.95	-
aspect sig. level	***	***	
SOIL CATEGORY			
Brown earth	-	-	2.18
Podsol	-	-	-0.30
Iron pan	-	-	-0.09
Peaty gley	-	-	0.06
S. W. gley	-	-	1.02
Basin bog	-	-	-1.17
Flushed peat	-	-	-0.55
Unflushed peat	-	-	-2.03
Skeletal	-	-	0.84
soil sig. level	-	-	***
TOTAL R^2 %	77.5	76.2	74.7

() figures in brackets indicate illogical values usually due to low numbers of observations in that category.

Table 14a. (cont)

VARIABLE	COEFFICIENT		
Model No	52	53	54
CONSTANT	19.25	20.95	19.75
ELEVATION	-	-0.0320	-0.0330
TATTER	-1.02	-	-
TATTER S.L.	-	-1.02	-1.090
ACC. TEMP.	0.0083	-	-
ACC. TEMP. S.L.	-	0.0081	0.0082
TOPEX	-	0.0332	0.0354
SLOPE	-0.107	-	-
SIN ASPECT	-	1.17	-
COS ASPECT	-	0.328	-
CROP AGE	-0.127	-0.109	-0.121
ASPECT CATEGORY			
N	-	-	0.74
NE	-	-	0.52
E	-	-	1.95
SE	-	-	(-1.54)
S	-	-	1.01
SW	-	-	-0.49
W	-	-	-0.74
NW	-	-	-0.93
LEVEL - VALLEY	-	0.97	1.05
LEVEL - HILL	-	-1.73	-1.41
aspect sig. level		***	***
SOIL CATEGORY			
Brown earth	2.21	2.04	2.95
Podsol	-0.14	0.28	0.11
Iron pan	0.17	0.41	-0.09
Peaty gley	-0.04	0.36	0.09
S. W. gley	0.70	1.07	1.36
Basin bog	-0.96	-2.15	(-2.09)
Flushed peat	-0.65	-0.44	-0.77
Unflushed peat	-1.97	-1.89	-1.63
Skeletal	0.65	0.35	(1.90)
soil sig. level	***	**	**
TOTAL R^2 %	77.6	79.3	81.6

Table 14b. Coefficients and R^2 values for models including categorical variables aspect and soil type; plots with standard silviculture.

VARIABLE	COEFFICIENT		
Model No	55	56	57
CONSTANT	19.11	19.46	18.98
ELEVATION	-0.0369	-	-0.0367
TATTER	-	-1.11	-
TATTER S.L.	-1.21	-	-1.20
ACC. TEMP.	-	0.0097	-
ACC. TEMP. S.L.	0.0114	-	0.0113
TOPEX	0.0399	-	0.0466
SLOPE	-	-0.108	-
SIN ASPECT	0.822	-	-
COS ASPECT	0.352	-	-
CROP AGE	-0.124	-0.153	-0.141
ASPECT CATEGORY			
N	-	-	1.01
NE	-	-	(0.08)
E	-	-	1.87
SE	-	-	(-1.89)
S	-	-	1.09
SW	-	-	-0.32
W	-	-	-0.30
NW	-	-	-0.68
LEVEL - VALLEY	-0.03	-	0.30
- HILLTOP	-1.79	-	-1.19
aspect sig. level	***		***
SOIL CATEGORY			
Brown earth	1.65	2.38	3.01
Podsol	-0.54	-0.86	(-0.68)
Iron pan	-0.66	-0.96	-1.14
Peaty gley	0.42	0.21	0.07
S. W. gley	0.89	0.86	1.15
Basin bog	-1.92	-1.07	(-1.98)
Flushed peat	-0.31	-0.54	-0.77
Unflushed peat	-1.72	-1.97	-1.39
Skeletal	(2.29)	(1.91)	(1.17)
soil sig. level	**	***	***
Total R^2 %	83.9	83.8	86.6

() figures in brackets indicate illogical values usually due to low numbers of observations in that category.

Table 15. Coefficients for models including categorial variables PWD and Oceanity.

VARIABLE	COEFFICIENT			
CONSTANT	19.4	18.7	17.9	17.8
ELEVATION	-0.0347	-	-0.0334	-
TATTER	-	-1.04	-	-1.01
TATTER S.L.	-1.20	-	-1.14	-
ACC. TEMP.	-	0.0098	-	0.0096
ACC. TEMP. S.L.	0.0102	-	0.0105	-
TOPEX	0.0416	-	0.0443	-
SLOPE	-	-0.078	-	-0.082
CROP AGE	-0.11	-0.115	-0.111	-0.116
PWD CATEGORY				
1 (-25 - 50 mm)	0.57	-0.16	-	-
2 (0 - 25 mm)	0.14	0.20	-	-
3 (0 - 500 mm)	-0.11	-0.24	-	-
4 (> 500 mm)	-0.61	0.11	-	-
PWD sig. level	NS	NS	-	-
OCEANITY CATEGORY				
1 (Hyper)	-	-	-0.19	-0.32
2 (Eu)	-	-	0.56	0.66
3 (Hemi)	-	-	-0.37	-0.34
Oceanity sig. level			*	**
R^2	71.8%	74.9%	72.1%	75.0%

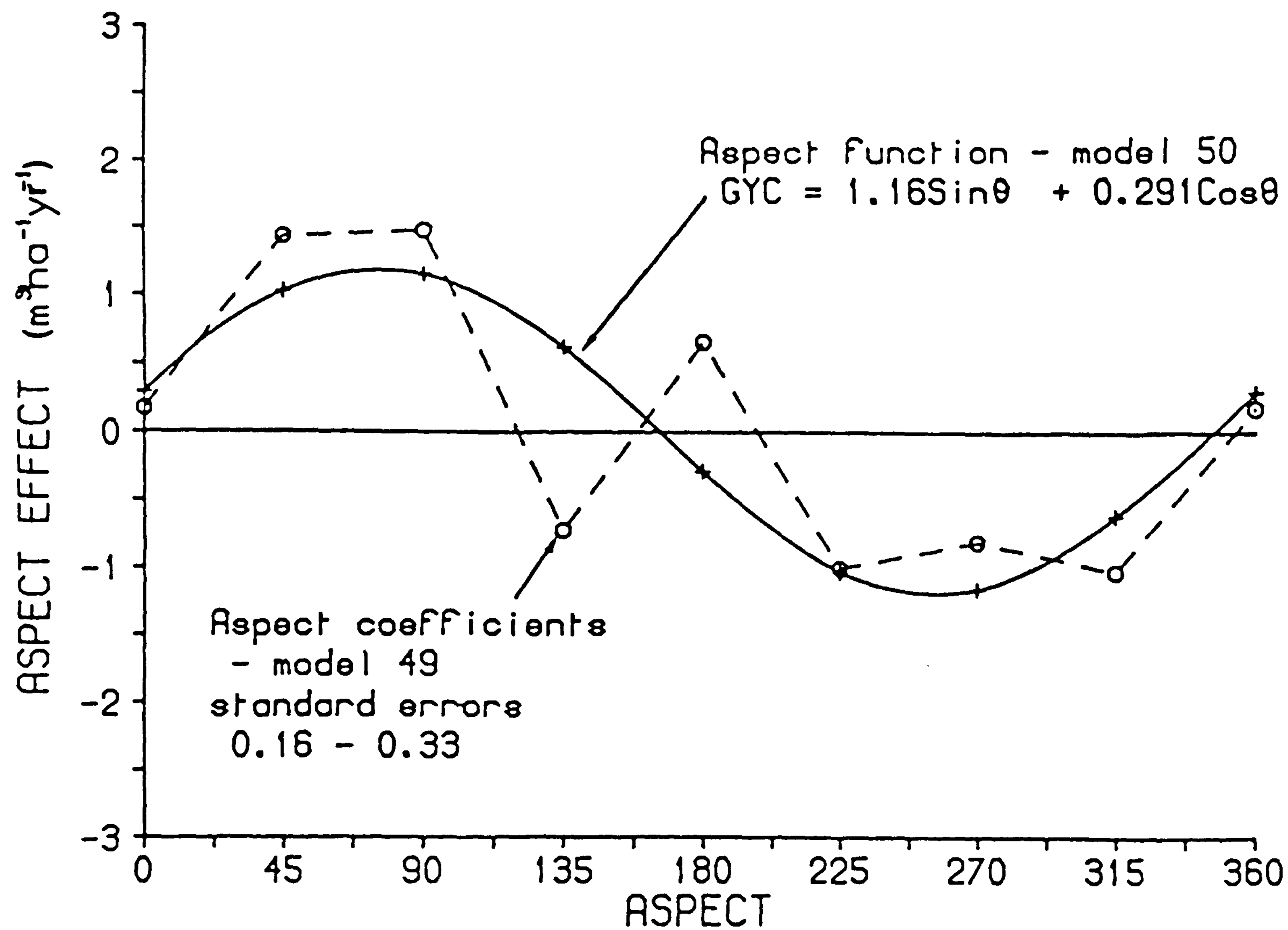


Figure 25. Effects of aspect on productivity

of categorical variables included is large compared with the number of observations, with the result that a number of slightly aberrant values occur.

The effects of aspect were also estimated by separating out level sites (valley bottom and hilltop) using dummy variables and applying trignometric transformations to the angle of aspect of the remaining sites (see models 50, 53, and 55). The trignometric function for model 50 is plotted in Figure 25.

The aspect effects shown in Table 14 and Figure 25 show that growth rates are higher on sites with easterly aspects than those with westerly aspects. These differences were statistically significant ($P < 0.001$) and increased the r^2 values of the models to 77 - 86 per cent.

Comparison of Figure 25 with Figure 16 shows that the distribution of productivity with respect to aspect follows a pattern converse to the pattern of windiness (tatter rate). This analysis indicates that wind is the most important factor in determining the growth rates of tree with respect to aspect and apparently dominates any effect of increased solar radiation which might have been expected to lead to increased productivity on south facing slopes.

5.3.3.2 Soil type.

Nine categories were used to estimate the effects of soil type according to the Forestry Commission soil classification (Pyatt 1982) ie. brown earths (BE) podsols (POD), iron pan (IP), peaty gley (PG), surface water gley (SWG), basin bog (BB), flushed peat (FP), unflushed peat (UP), and skeletal soils (SK).

Table 14 and Figure 26 show the effects of the different soil types in terms of their associated deviation from average in $m^3\ ha^{-1}\ yr^{-1}$. These differences were significant ($0.01 < P < 0.001$), despite the inclusion of soil type only increasing the r^2 values by 2 - 4 per cent.

Reference to Figure 26 shows that the most productive soils are brown earths (approx +2 $m^3\ ha^{-1}\ yr^{-1}$) followed by surface water gleys (+1 $m^3\ ha^{-1}\ yr^{-1}$). Podsols, iron pans and peaty gleys all gave values close to average. Basin bogs gave values of about -1.5 $m^3\ ha^{-1}\ yr^{-1}$ but these were based on only two observations. Flushed peats showed values around -0.5 $m^3\ ha^{-1}\ yr^{-1}$ and unflushed peats values around -2 $m^3\ ha^{-1}\ yr^{-1}$. Skeletal soils give, somewhat surprisingly, values of about +0.5 $m^3\ ha^{-1}\ yr^{-1}$, but this value is

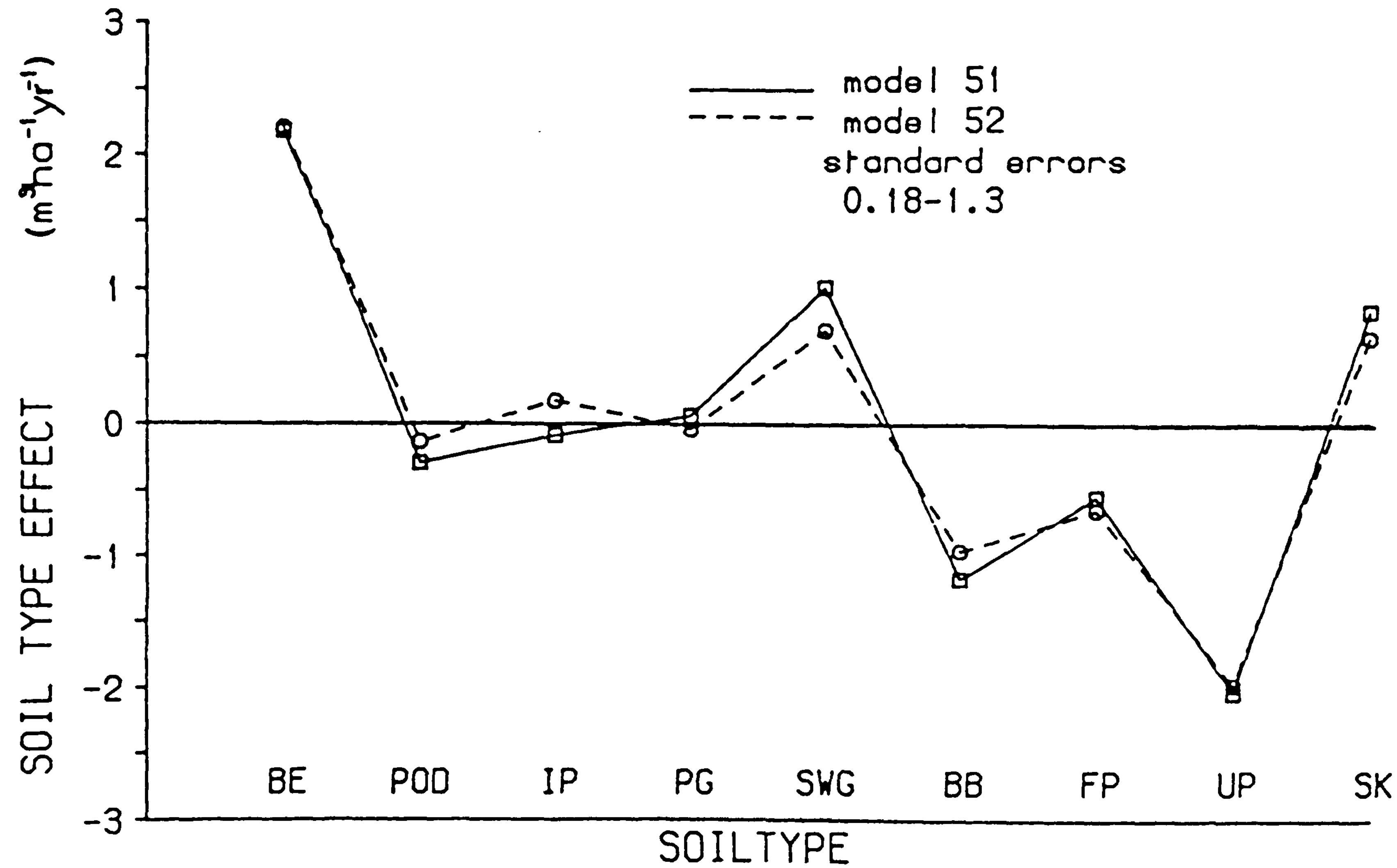


Figure 26. Effects of soil type on productivity

based on very few observations. The total range ie. from +2 to −2 $m^3\ ha^{-1}\ yr^{-1}$ does not appear to be very large but it should be remembered that this is variation which is accounted for after climatic and some of the topographic effects have been included.

5.3.3.3 Potential water deficit.

Potential water deficit (PWD) was included to test for possible detrimental effects of either deficient or excessive rainfall on productivity (see section 2.1.4.3). No significant differences were apparent when the four PWD classes were introduced as categorical variables into models 44 and 46 (see Table 15). PWD was not included in further regression analysis.

5.3.3.4 Oceanicity.

Oceanicity was included to test for possible effects due to the distribution of growing season warmth throughout the year, oceanic climates being characterised by relatively long and cool growing seasons in comparison with more continental ones (see section 2.1.4.3). Table 15 shows that significant differences between the oceanicity classes did occur ($P < 0.05$), with the highest productivity values being recorded in the intermediate "euoceanic" class. This result is contrary to view that the productivity of Sitka spruce increases as the oceanicity of the climate increases. However the differences between the classes were relatively small and increases in r^2 values achieved by including oceanicity were less than 1 per cent. For these reasons it seemed that oceanicity was not a particularly useful variable for explaining the remaining variation in GYC and it was not included in further models.

5.3.4 The best regression models.

Multiple regression analysis has demonstrated that the productivity of Sitka spruce is related to the following site variables:

1. Climatic − accumulated temperature and windiness. These effects are mediated by both increasing elevation and geographical location.
2. Topographic − geomorphic shelter and aspect, apparently through their effect on wind-climate.
3. Crop age.

4. Soil type.

Models 51 to 57 (Table 14) include all these effects and account for 75 per cent to 82 per cent of the variation in GYC for the complete data set and 84 to 86 per cent of the variation in GYC for plots having received standard silvicultural treatment.

Two basic forms of model can be employed. Firstly the effects of the climatic and topographic variables can be estimated by the two variables "estimated tatter rate" and "estimated accumulated temperature" (models 52 and 56). This gives a fairly rational and expedient basis for a model. However, the process of extrapolation by which these values are arrived at introduces sources of error to the model the magnitude of which are largely unknown. Further, estimates of the effect of geomorphic shelter and aspect are included solely through their effects on estimated tatter rate. Although there is good evidence indicating that the effects of geomorphic shelter and aspect on GYC are closely related to their effects on wind conditions, this is obviously an oversimplification.

Alternatively models can be developed based on elevation and the sea-level values of estimated tatter rate and estimated accumulated temperature (models 53, 54, 55 and 57). Although there are also errors attached to these values, the effects of elevation, geomorphic shelter and aspect can be included independently in the subsequent regression analysis, thus largely excluding the extrapolation process as a source of error. Models 53 and 55 present the effects of the various factors in a way which is easily adaptable for practical use and in which all the coefficients are logical (with the possible exceptions of the values for basin bogs and skeletal soils which were based on only a few observations).

Models 54 and 57 whilst explaining more of the variation in GYC than the other models also include several apparently slightly aberrant coefficients due to the relatively high number of categorical predictor variables in relation to the number of observations. This is particularly true of the model based on the data from plots having received standard silvicultural treatment.

Models 52, 53, 55 and 56 were selected as giving the most reliable and complete picture of the relationships between the site factors and productivity.

The regression analyses and analyses of variance for these models are given in Appendix 7. The following sections describe assessment of the precision of these equations and their validation using a new set of observations.

5.3.5 Confidence Limits.

Confidence limits for multiple linear regressions can be given by the following generalised equation:

$$C.L. = Y' \pm t\sqrt{\{s^2 + R/m\}} \quad \ldots\ldots\ldots (58)$$

s = standard deviation of fitted y-value

R = residual mean square of regression equation

m = no. of new observations with a specific combination of x-values to which the confidence limits are to apply.

Standard texts on regression analysis (eg. Freese 1964, Mead and Curnow 1983) often highlight two special cases of this (or similar) equations, namely the case when m is equal to infinity and that when m = 1. In the first case, the term R/m becomes zero and the confidence limits apply to the estimate of the mean y-value for all cases in the population which has been sampled with the specified combination of x-values. This is equivalent to the confidence limits for the regression equation, the confidence limits giving the range of values within which the true relationship lies with a probability of 95 in 100. The second case where m=1 gives confidence limits (prediction limits) which apply to the predicted y-value of a single new observation. These limits are wider than the confidence limits for the regression line because they take account of the variation of the individual observations about their mean for the specified combination of x-values.

In previous studies of the relationships between productivity and site factors the confidence limits calculated on the basis of m=infinity have often been applied (eg. Cook et al. 1977, Blyth 1974a), presumably because it was considered relevant to give an estimate of the mean productivity and accompanying confidence limits for *all* the land in the sample population with specific combinations of x-variables. In the case of this study, prediction of the mean productivity for all the land (in Scotland and N.England) is not considered to be a relevant consideration as land is generally bought and managed in smaller blocks. The estimates of productivity for these smaller blocks will have a greater amount of variability attached to them than the estimates of mean productivity. Equally predictions based on a single 0.04 ha plot are not considered to be particularly relevant because this is a far smaller area than any practical management unit.

The picture is further complicated by the fact that some of the residual variation in the models may be site-related ie. certain sites (locations) may be associated with specific values of error. In this context it should be realized that prediction of productivity will almost always be carried out for a specific site (location) rather than for areas of land distributed throughout Scotland and northern England.

As a first step in deciding appropriate confidence limits for application of the best models in a practical context it was assumed that the error variance was not site-related. An area of land for which a prediction of productivity is required may be considered as an agglomeration of m 0.04 ha plots and the appropriate confidence interval can be calculated by applying equation 58 above. Confidence limits for the "best" regression models (52, 53, 55 and 56) were calculated for the cases m=1 (prediction limit for individual observation) and m=infinity (c.l. for regression line) with the x values set both at mean values and at extreme values (see Table 16). To illustrate the way in which the confidence limits change with changing values of m, confidence limits for model 53 were also calculated for values of m between 1 and 250 (see Figure 27).

The width of the confidence limits declined rapidly with increasing values of m until by a value of 25 (which is equivalent to an area of one hectare) the value is ± 1.0 m^3 ha^{-1} yr^{-1} for mean values of X and 1.4 for extreme values of X.

The second step was then to test for the existence of a site-related component of the error variance which would increase the error of predicted values of productivity for specific locations. This was done by fitting a model with all the appropriate predictor variables, *plus* dummy variables for each of the 37 sites (locations). This was carried out for the models based on the

Table 16. Estimates of precision for the best regression models.

	MODEL 53	MODEL 55	MODEL 52	MODEL 56
Residual mean square	3.59	3.16	3.77	3.05
Standard deviation fitted Y-value				
mean values of X	0.336	0.386	0.250	0.323
extreme values of X	0.592	0.691	0.636	0.658
Confidence limits of regression line (m = infinity)				
mean values of X	±0.66	±0.76	±0.50	±0.64
extreme values of X	±1.17	±1.37	±1.25	±1.30
Prediction limits for single observation (m = 1)				
mean values of X	±3.80	±3.61	±3.86	±3.51
extreme values of X	±3.91	±3.78	±4.03	±3.70
Confidence limits for a single site				
mean values of X	±2.29	-	±2.31	-
extreme values of X	±2.48	-	±2.58	-
Mean deviation of predicted from actual GYC for a single site				
mean values of X	±0.93	-	±0.94	-
extreme values of X	±1.01	-	±1.05	-
overall average	±0.97	-	±1.01	-

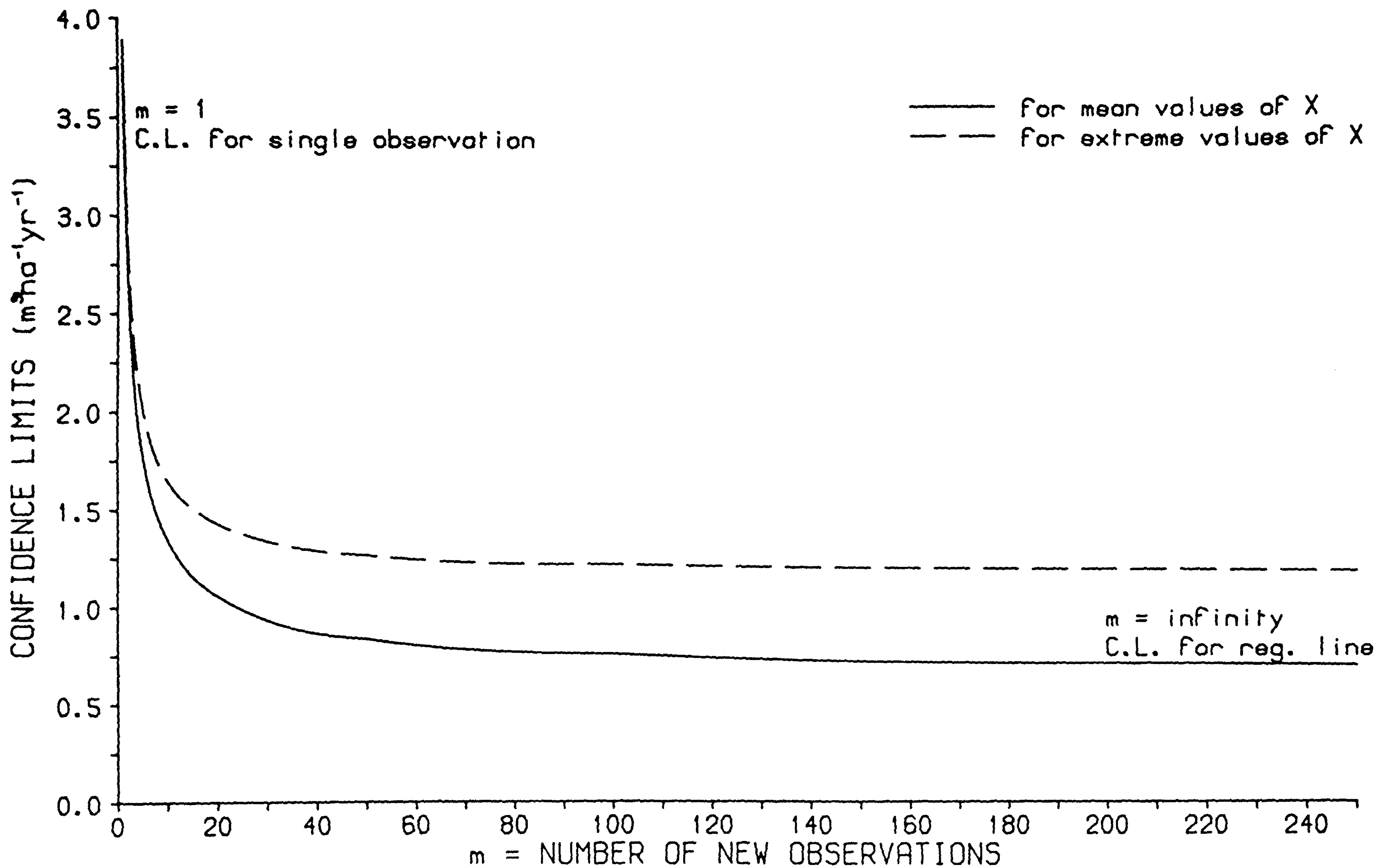


Figure 27. Change in confidence limits for model 53 with increasing values of m

complete data set (models 52 and 53). The following section describes the calculations for model 52 and gives the results for model 53 which were calculated in an identical fashion (see Appendix 7 for regression analyses).

The amount of variation accounted for by the set of dummy variables for site (location) was calculated and tested against the residual mean square in the normal way. The f-value was:

$$f = \frac{\text{sum of squares (site)}}{(n-1)\text{RMS}} = \frac{232.95}{36(3.77)} = 2.386 \text{ (36 and 139 d.f.)}$$

where n = number of sites

RMS = residual mean square (see Table 16)

The f-value was highly significant demonstrating that a proportion of the variance was site-related. This means that the variance can be regarded as having a between-site (location) component and a within-site component. The between-site component will have a value which can be considered as being independent of the number of new observations (m) whereas the within-site component will be reduced as m increases in a similar fashion to that described in the preceding section. This can be expressed as follows:

Error of predicted Y = $E_x + S_l^2 + S_p^2/m$

where E_x is the error associated with the estimates of the coefficients for the predictor variables.

S_l^2 is the site related component of error

S_p^2 is is the within site error

m is the number of observations (= area of land) to which the prediction applies

The quantities S_l^2 and S_p^2 can be estimated from the analysis of variance from model 52 above in the following way:

SOURCE	DF	SS	MS	ERROR MS
Regression	11			
Error				
Sites (locations)	36	323.95	8.999	$S_p^2 + qS_l^2$
Within sites	140	335.41	2.394	S_p^2
Total Error	176	659.09	3.745	

where S_l^2 is between site error variance

S_p^2 is within site error variance

and $$q = \frac{1}{k-1} \sum Ni - \frac{\sum Ni^2}{\sum Ni} = 4.98$$

where k = number of sites

Ni = number of plots at i'th site

From this it is possible to estimate S_l^2 as follows:

$$S_l^2 = \frac{(8.999 - 2.394)}{4.98} = 1.326$$

The effective variance on which to base confidence limits is then:

$$\text{Var } Y' = S_f^2 + S_l^2 + S_p^2/m$$

where S_f^2 is the standard deviation of the fitted y value (Table 16)

Because the area of land for which any prediction will be made will be vastly larger than the size of the original plots, m will always be very large and the term S_p^2/m will be very small and for practical purposes can be ignored. Appropriate confidence limits with X values set at mean levels are therefore:

$$Y' \pm t\surd\{S_f^2 + S_l^2\}$$

$$= 13.9 \pm 1.96\surd\{0.0625 + 1.326\} = 13.9 \pm 2.31$$

Similar calculations for sites with X-values at extreme levels gave confidence limits of ± 2.6 m^3 ha^{-1} yr^{-1} (see Table 16) . Thus the 95 per cent confidence limits for the prediction of GYC for a specific site (aquisition) are between 2.3 and 2.6 $m^3\ ha^{-1}\ yr^{-1}$. The mean deviation of the predicted values from the actual values (assuming normally distributed values of Y') can be given by multiplying the standard error of the predicted Y value by the ratio:

$(2/\pi)^{-2}$ (Moran 1968)

This gives a value for mean deviation of predicted values from actual values *for one site* (based on mean values of X) of $\pm 0.94\ m^3\ ha^{-1}\ yr^{-1}$. The corresponding values for extreme X-values are $\pm 1.05\ m^3\ ha^{-1}\ yr^{-1}$. This level of precision is probably adequate for the models to be of use in practical applications in forestry.

5.3.6 Validation of regression models.

Validation of the regression models was carried out by recording values of productivity (GYC) and the relevant site factors for 36 new sample plots from 14 forests in Scotland. The plots were chosen by local Forestry Commission research staff to be representative of the growth of Sitka spruce on upland sites at various elevations within their regions and to be free from serious establishment problems (heather check, frost, waterlogging). The data are shown in Appendix 8a. The observed values of GYC for each plot and those predicted by models 52, 53, 55, and 56 are shown in Appendix 8b, and are summarised in Table 17 and Figure 28 below. Values predicted by the Forestry Commission site-yield guide (Busby 1974) are also shown. The relationship between actual and predicted GYC for model 53 is shown in Figure 28 and corresponding values predicted by Busby (1974) are shown in Figure 29. Two of the observations were treated as outliers because the GYC values deviated widely from predicted values and were considered as unrepresentative (GYC 24 on deep peat on an exposed site in Caithness, and GYC 9 on a flushed peat at 200 m at Sunart).

Table 17 shows the mean deviations (actual minus predicted GYC) for the single plots, for the forests (with > 1 plot) and for all the plots combined. Values are given excluding the two observations considered as outliers. The predictions of GYC for the 32 single plots varied from the observed values by on average $\pm 1.48 - 1.76\ m^3\ ha^{-1}\ yr^{-1}$, those for the 9 individual forests varied by $\pm 1.01 - 1.28\ m^3\ ha^{-1}\ yr^{-1}$ and the mean for all the plots differed from the true mean by 0.02 to $-0.67\ m^3\ ha^{-1}\ yr^{-1}$. This compares with figures of about

Table 17. Results of validation exercise.

MEAN ACTUAL YIELD CLASS = 15.83

	Model 53	Model 55	Model 52	Model 56	Busby
MEAN PREDICTED YIELD CLASS	15.66	15.85	15.15	15.46	11.71
MEAN ERROR (ALL PLOTS)	0.17	0.02	-0.67	-0.36	-4.12
MEAN DEVIATION OF SINGLE PLOTS	1.48	1.53	1.76	1.70	4.39
MEAN DEVIATION OF FOREST MEANS	1.01	1.05	1.28	1.20	2.65
R^2 VALUE FOR REGRESSION ACTUAL GYC VS PREDICTED GYC	64.1	62.7	63.6	63.3	6.8

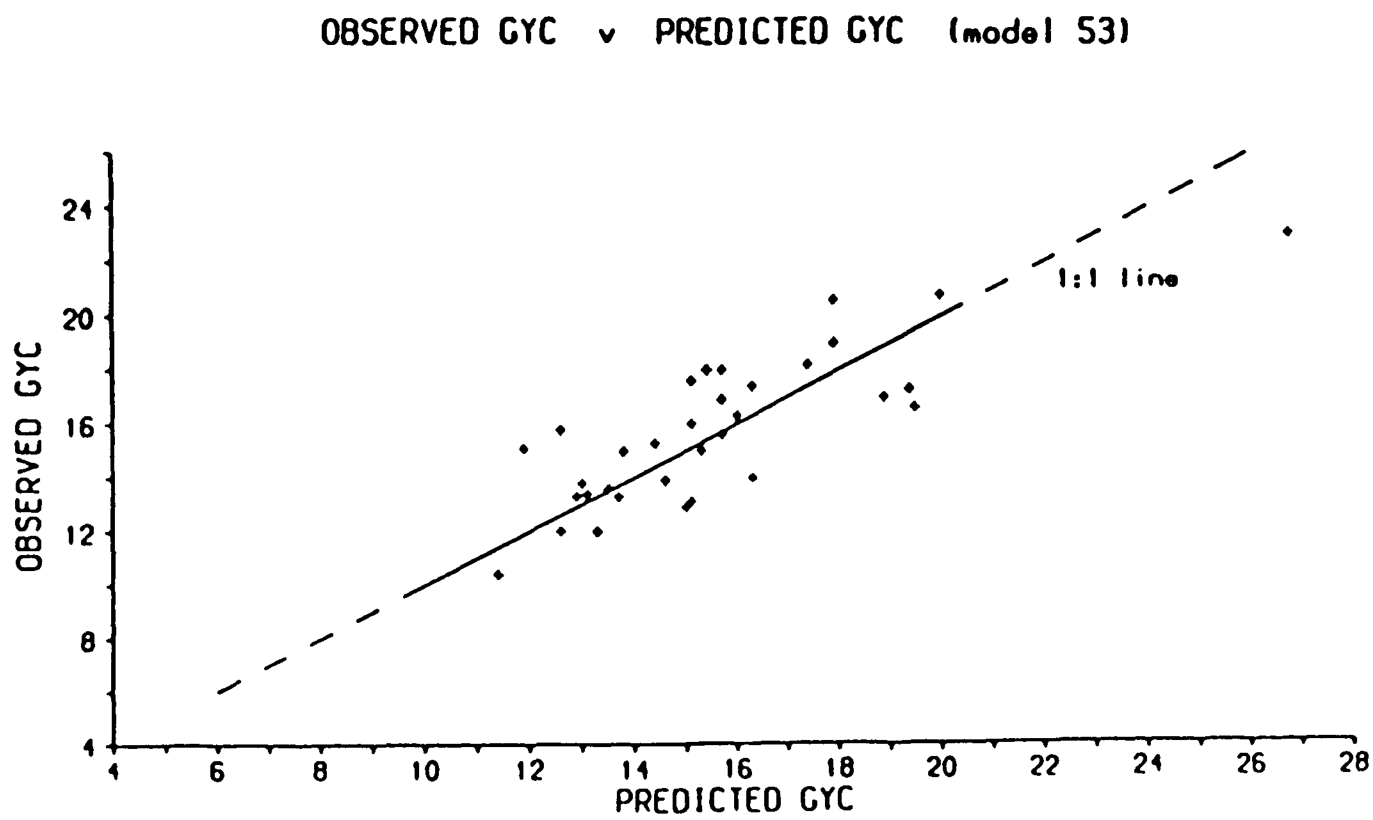


Figure 28. Relationship between observed GYC and predicted GYC (model 53)

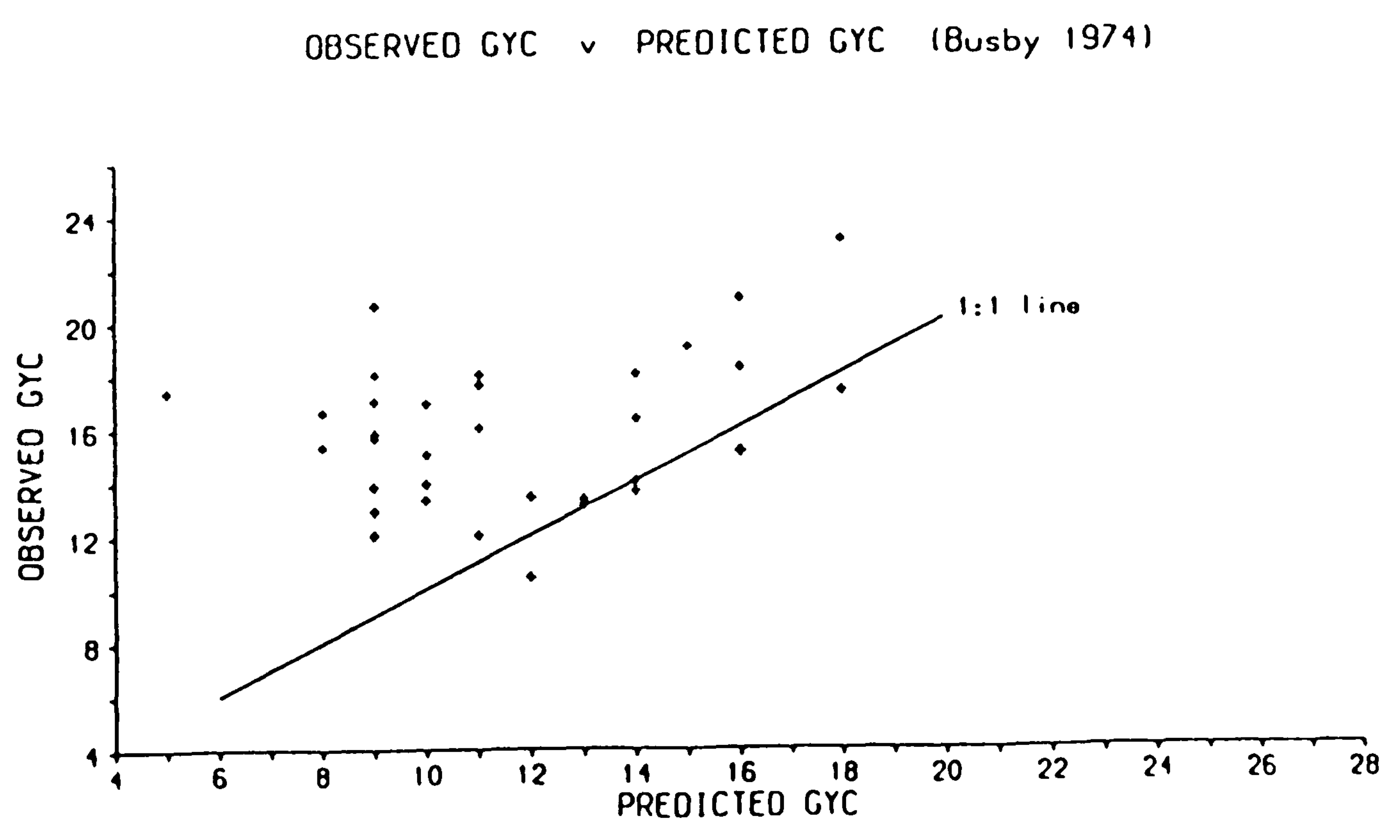


Figure 29. Relationship between observed GYC and values predicted by Busby (1974)

±4.4, ±2.65 and a mean error of - 4.1 m^3 ha^{-1} yr^{-1} for estimates derived from the site/yield guides published by the Forestry Commission (Busby 1974). It should be noted that the estimates given by Busby (1974) are for whole compartments and therefore contain an intentional element of underestimation. Table 17 also gives the r^2 values for the regressions of actual GYC on predicted GYC. These were close to 63 per cent for all the models, which is somewhat lower than the values for the equations from the original data. The r^2 value for the regression using estimates from Busby (1974) was only 6.8 per cent (see Figure 29).

These values of mean deviation for the individual forests are similar to those predicted by analysis of the standard error of the regression models (see section 5.3.5). Thus for a single location (forest block) the best regression models in this study would apparently predict GYC with a mean error of about ± 1 m^3 ha^{-1} yr^{-1}. With the possible exception of the "experienced local forester", this represents a considerable improvement over existing methods of yield prediction.

5.4 Principal component analysis.

Principal component analysis (PCA) and factor analysis are forms of multivariate analysis which have occasionally employed in investigations of forest site-growth relationships (eg. Malcolm 1970, Blyth 1974a, Cook 1971, Hunter and Gibson 1984). Such techniques have also been employed in ecological studies of the relationships between site and vegetation (eg. Gittins 1969). The advantages cited by users of these techniques include:

1. They provide a useful exploratory technique when correlations between a relatively large number of variables are being investigated.
2. They provide a method of reducing a large number of inter-related variables to a smaller number of components.
3. The components are orthogonal and can therefore be used in subsequent regression analysis.

In the context of site-growth relationship studies the disadvantages of these techniques are:

1. They are very susceptible to changes in scales of measurement.
2. Interpretation of the results for practical purposes can be problematic.
3. It is more difficult to construct predictive models from the results than when using regression analysis.

Principle component analysis uses as input the deviations of the values of variables from their means, usually in the form of correlation or covariance matrices. For this reason the technique is essentially similar to correlation and regression techniques. In this study a limited amount of PCA was carried out with the aim of presenting the correlations between the variables in a more informative fashion and confirming the choice of variables made using regression techniques.

Principal component analysis was carried out for the complete data set in the following stages:

1. Calculation of a correlation matrix.
2. Calculation of the component loadings, latent roots and the amount of variance associated with each component.
3. Regression of GYC against the component scores using stepwise regression techniques.

The variables included were GYC, elevation, topex, slope, windzone, estimated accumulated temperature, estimated tatter rate, estimated rainfall, PWD (class) and oceanicity (class).

Table 18 shows the component loadings, latent roots and the amount of variance explained for the components with latent root exceeding a value of 1. Component 1, which explains the greatest amount of variation in the data, shows high values of loadings for the variables topex, slope, rainfall and PWD. The value for GYC is relatively small. This indicates that that the data is well separated by these variables but that they are not immediately related to GYC. Component 2 shows high values of loadings for GYC, elevation, tatter rate and accumulated temperature indicating strong relationships between them. Component 3 shows high values of loadings for GYC, windzone, tatter rate and

Table 18. Latent vectors, loading and percentage variance accounted for by six components.

VARIABLE	COMPONENT 1	2	3
GYC	-0.182	-0.359	-0.410
Elevation	0.279	0.423	-0.024
Topex	0.408	-0.262	-0.043
Slope	0.397	-0.097	-0.042
Windzone	0.257	0.254	-0.458
Tatter rate	-0.167	0.433	0.403
Acc. temperature	-0.242	-0.439	-0.015
Age	0.338	-0.235	-0.048
Rainfall	0.373	-0.185	0.282
PWD (class)	0.381	-0.053	0.236
Oceanity (class)	0.115	0.277	-0.563

	C1	C2	C3	C4	C5	C6
LATENT ROOT	4.34	3.11	1.45	(0.74)	(0.42)	(0.38)
% VARIANCE	39.5	28.3	13.2	6.7	3.8	3.5
CUM % VARIANCE	39.5	67.8	81.0	87.7	91.5	95.0

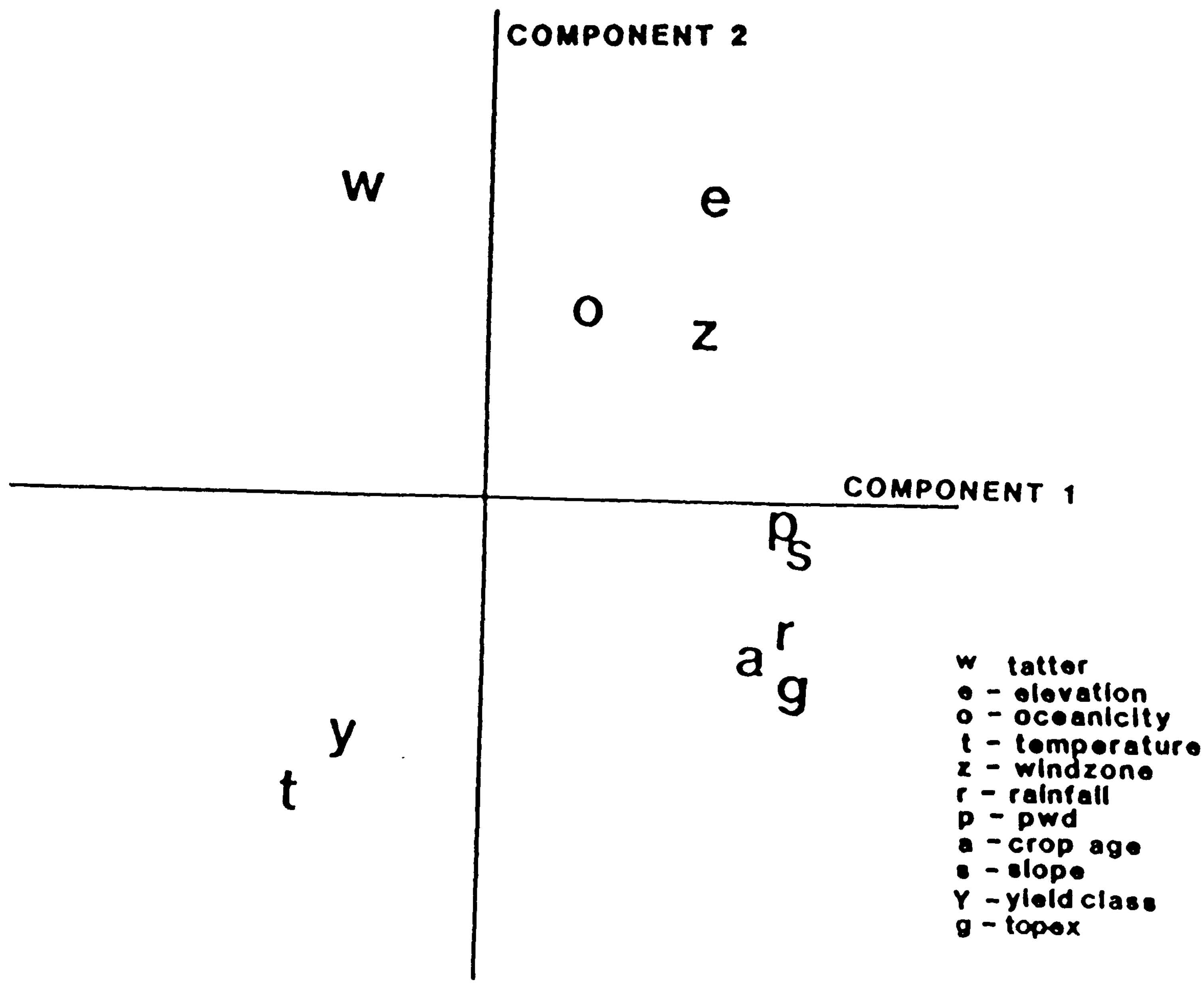


Figure 30. PCA loadings, component 1 against component 2

oceanicity.

The loadings on component 1 plotted against the loadings on component 2 is shown in Figure 30, which displays many of the more important results of the correlation analysis (see section 5.2) in diagrammatical form. The close relationships between topex, slope, rainfall, PWD and age described in section 5.2 are apparent. The low loadings of these variables on component 2 indicates that these factors are relative poorly related to GYC, elevation, tatter rate and accumulated temperature. The close relationship between GYC and accumulated temperature is apparent as well as negative relationships between GYC and elevation, GYC and tatter rate, and temperature and elevation. Elevation and windzone are positively related due to exposed areas occurring at increasingly high elevation with increasing windzone number.

Figure 31 shows highest and lowest component scores for each of the sites for components 1 and 2. This gives a diagrammatic representation of the main characteristics of the sites. For example the lowest yielding and highest elevation sites are located in the top right-hand corner of the diagram (Queens, Torrachilty,) whereas the lowest elevation and highest yielding sites are at the bottom left-hand side of the diagram (Ratagan). The sites with high topex, slope, rainfall, PWD and age are Glenshiel, Ballachulish, and Sunart, these contrasting with sites such as Deer, Rumster, Lewis and Borgie which have low values of topex, slope, and age and are relatively dry sites (for this data set). This gives a relatively clear picture of the major relationships in the data and indicates the characteristics of the different sites which have given rise to them.

Stepwise regression analysis was carried out of GYC against component scores produced by PCA excluding GYC as a variable. The results are shown in Table 19. The first component chosen was component 2 which can be interpreted as an expression of elevation, accumulated temperature and windiness. The second component was component 3 which includes the effect windiness, windzone (positively correlated with GYC) and moisture regime of the sites (increasing rainfall being negatively related to GYC). The increase in r^2 values as the different components are included is only modest and this analysis certainly does not provide a superior method of constructing models to that of regression analysis shown in section 5.3. The choice of variables made using PCA (elevation, accumulated temperature and tatter rate) confirms

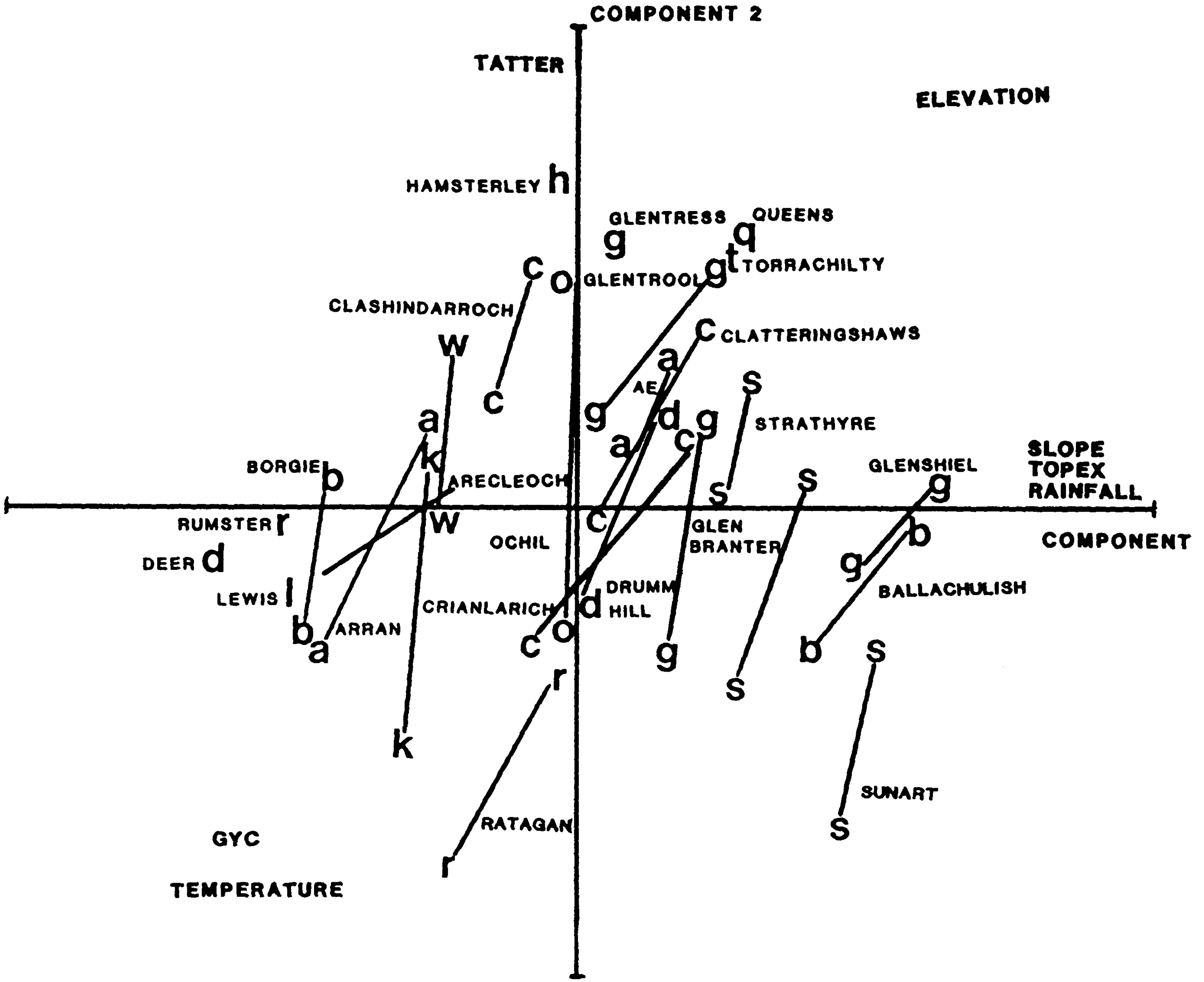


Figure 31. PCA loadings for individual sites

Table 19. PCA excluding GYC for complete data set and stepwise regression results for GYC against components 1-6.

VARIABLE	COMPONENT C1	C2	C3
Elevation	0.231	-0.491	0.149
Topex	0.439	0.201	-0.077
Slope	0.407	0.046	0.030
Windzone	0.241	-0.376	-0.306
Tatter rate	-0.227	-0.369	0.523
Acc. temperature	-0.188	0.434	-0.115
Rainfall	0.390	0.161	0.337
PWD (class)	0.386	0.006	0.378
Oceanity (class)	-0.370	-0.370	-0.547

	C1	C2	C3	C4	C5	C6
LATENT ROOTS	4.24	2.78	1.23	(0.59)	(0.40)	(0.37)

STEPWISE REGRESSION ANALYSIS OF GYC ON SIX COMPONENTS

GYC = 13.96 + 16.9(C2) - 21.0(C3) + 27.6(C4) - 6.6(C1) - 18.3(C6) - 12.5(C5)

CHANGE IN R^2 DUE TO ADDITION OF EACH COMPONENT

	R^2	Change
Component 2	26.6	26.6
Component 3	44.7	18.1
Component 4	59.7	15.0
Component 1	65.9	6.2
Component 6	70.1	4.2
Component 5	72.1	2.0

the choices made using regression analysis.

5.5 The effects of elevation on tree form.

Previous studies have indicated that a relationship exists between elevation and the height to diameter ratio of trees in windy climates (Malcolm and Studholme 1972, Hughes 1979). This is considered to be the result of the action of wind both in redistributing stem diameter increment (Hughes 1979) and (at least in the case of Sitka spruce in Britain) in causing repeated loss of height increment by leader breakage.

In this study there was only a poor relationship between H/D ratio of the top height trees and elevation, with elevation explaining only 11 percent of the variation in H/D ratio. The relationship is shown below:

$$H/D = 65.0 - 0.0254(\text{elevation}) \qquad R\text{-sqd} = 11.1\%$$

A better relationship was obtained between H/D ratio and estimated tatter rate, indicating that wind is indeed the main agent causing changes in tree form on high-elevation sites. Taper increased from H/D ratio values of about 70 on relatively sheltered sites to about 45 on exposed sites. The relationship is shown in Figure 32. Height to diameter ratio was also affected by the age of the crop, tending to increase with increasing age. The best relationship describing the increase in H/D ratio with decreasing site windiness and increasing crop age was:

$$H/D \text{ ratio} = 51.8 - 1.92(\text{tatter}) + 1.17(\text{age}) - 0.0139(\text{age})^2$$

$$R\text{-sqd } 58.3\%$$

5.6 The effect of site factors on Production Class and Local Yield Class.

The Production Class system provides a means of applying different top height/volume functions when estimating maximum mean annual increment (GYC) from the top height of crops. This is intended to take account of regional variations in the relationship between top height and tree volume. Production Class is applied as a positive or negative adjustment to general yield class (giving "local" yield class - LYC), General Yield Class being arrived at by using the *average* top height/volume function. A systematic increase in tree taper with increasing site elevation or windiness should be reflected in an increase in Production Class as the basal area of crops increases relative to

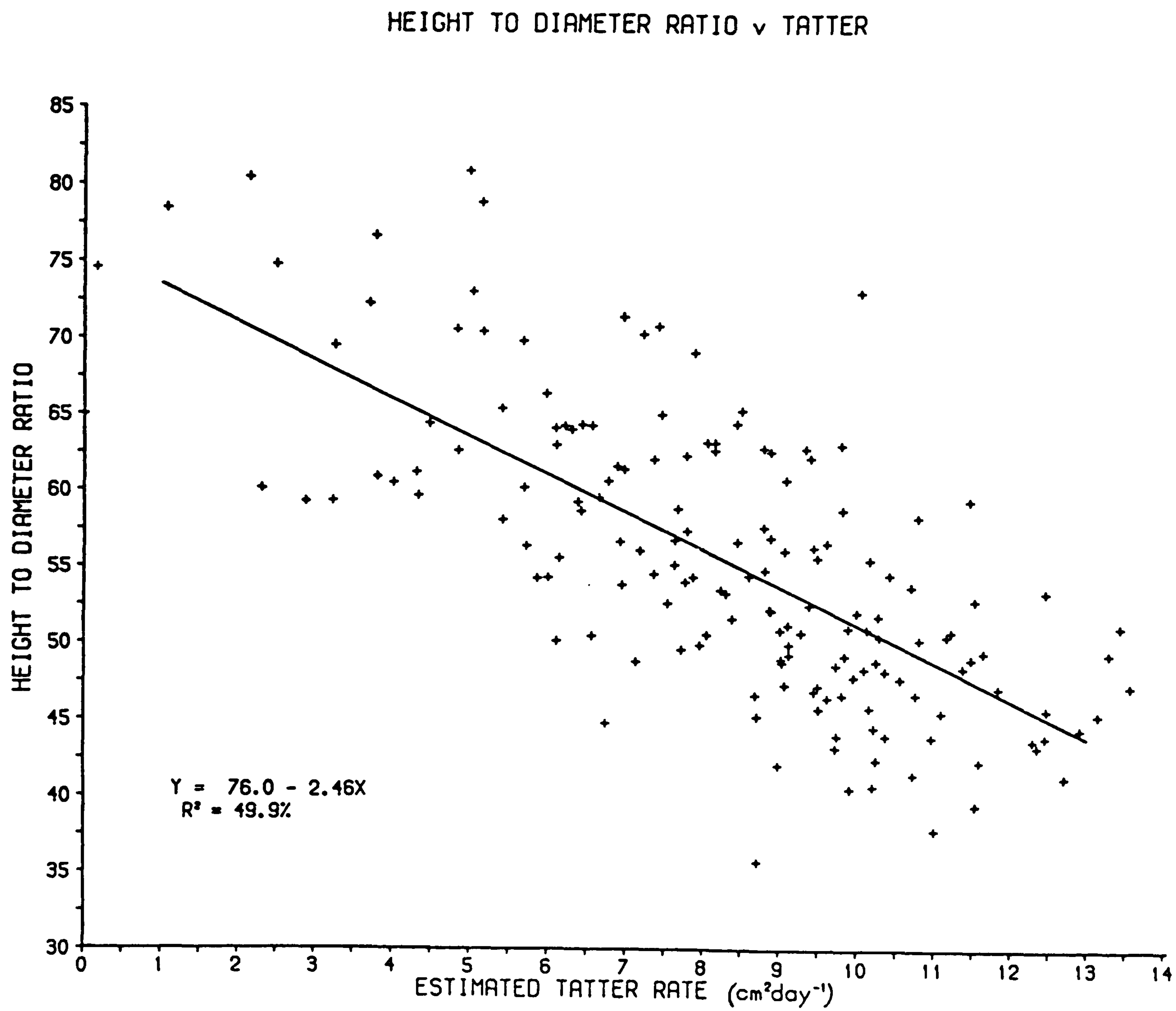


Figure 32. Relationship between height to diameter relationships of top height trees and estimated tatter rate

their top height.

Production Class in this study was arrived at with reference to the relationship between the top height and the cumulative basal area production of the crop (Edwards and Christie 1981). It was possible to estimate production class for 97 of the plots assessed in this survey. These were the crops which were unthinned and had top heights greater than 6 m (the minimum value for which Production Class functions are given).

Production Class varied fairly widely from plot to plot and showed an average value of 0.53 $m^3\ ha^{-1}\ yr^{-1}$. This indicates that the crops surveyed in this study have a modestly higher basal area for a given top height than the national average, and accordingly a slightly higher standing volume for a given top height. Production Class increased with increasing elevation but the relationship was not a close one, elevation accounting for 23 percent of the variation in Production Class.

$$\text{Production Class} = -3.36 + 0.0109(\text{elevation}) \qquad r^2 = 23.2\%$$

Rather surprisingly the relationship between Production Class and estimated tatter rate was very poor tatter rate accounting for only 12.2 per cent of the variation in Production Class. Stepwise regression analysis showed that Production Class was best related to elevation, stocking (n/ha) and estimated tatter rate, but even then the relationship was not close. The relationships were positive with all the variables as shown below:

$$\text{Production Class} = -9.02 + 0.0075(\text{elevation}) + 0.0015(\text{stocking}) + 0.29(\text{tatter}) \qquad r^2\ 38.0\%$$

The relationships between Production Class and environmental factors (and crop stocking) though present were poor. This is probably because the Production Class system is designed to be applied on a regional basis and should not strictly be applied to an area as small as a plot. Further it should only be applied to fully stocked and preferably older crops. Much of the variation in Production Class encountered in this study seems to stem from a high degree of variation in basal area growth in the plots, this variability being considerably greater than the corresponding variation in height growth of the top height trees (ie. GYC). This is because no attempt was made to locate the plots in areas of totally even stocking and growth as it was felt that this would give an unrepresentative picture of productivity on high elevation sites. As a result a high degree of spatial variation in basal area growth and stocking was encountered, particularly on the poorest sites and in young crops. This manifested itself as small gaps, areas of partially checked growth and in some areas very high stocking rates. The poor correlations described above indicate that application of the Production Class system to single plots in predominately young crops on high elevation sites stretches the system beyond the limits for which it was designed.

Local Yield Class for the 97 plots was only poorly correlated with site factors. Stepwise regression of LYC on all the site factors included in this study failed to give models which explained more than 40 per cent of the variation in LYC. These low levels of correlation result from the high degree of spatial variation in basal area growth described above.

5.7 Conclusions.

1. The productivity of Sitka spruce on upland sites is related to both climatic factors and soil type. The proportion of the total variation in productivity accounted for by climatic (and topographic) factors was high (70-78 per cent), whereas the contribution due to soil type was very modest (2-3 per cent). This probably reflects both the dominating influence of climatic factors on upland sites and the effects of site amelioration practices which are aimed at removing edaphic limitations to growth.

2. The climatic factors most closely related to productivity were measures of site temperature and site windiness. Productivity was apparently unrelated to estimates of site moisture status (rainfall and PWD class). Productivity, site windiness and site temperature are all closely related to elevation.

3. Productivity was related to the topographic factors topex and aspect, high levels of productivity being associated with areas of high geomorphic shelter and east facing aspects. This pattern is the converse of the results from the analysis of the tatter data (see section 4.2.4) indicating that the influence of topography on productivity is largely mediated by its effects on wind-climate. The was no apparent evidence of solar radiation causing higher levels of of productivity on south-facing as opposed to north-facing aspects.

4. Productivity was significantly negatively correlated with crop age. This is probably the result of the improved standards of silvicultural treatment on growth during the establishment phase of the crops.

5. Soil type was significantly related to productivity, the main soil types ordering themselves with respect to productivity as follows: brown earth > surface water gley > podsol, iron pan, peaty gley > flushed peat > basin bog, unflushed peat.

6. Regression equations were calculated which included climatic factors, topographic factors, soil type and crop age. These explained 75-86 per cent of the variation in productivity and could be used as a basis for the prediction of productivity. Confidence limits for the prediction of GYC for a specific site (acquisition) were ±2.3 - 2.6 m^3 ha^{-1} yr^{-1} and the *mean* deviation of predicted GYC from actual GYC was ±0.93 - 1.05 m^3 ha^{-1} yr^{-1}.

7. Comparison of the best models with validation data showed that the predictions of GYC for 32 single plots varied from observed values by an average of ±1.5 - 1.8 m^3 ha^{-1} yr^{-1}, for the 9 individual forests varied by ±1.0 - 1.3 m^3 ha^{-1} yr^{-1} and the mean for all the plots differed from the true mean by 0.02 to - 0.7 m^3 ha^{-1} yr^{-1}. This compares with figures of about ±4.4 , ±2.6 and a mean error of - 4.1 for estimates derived from site/yield guides published by the Forestry Commission (Busby 1974).

8. Increasing elevation and windiness were associated with increasing stem taper. The relationships between site factors and Production Class and Local Yield Class were not close due to a high degree of variation in basal area growth encountered in the crops surveyed.

CHAPTER 6

ESTIMATING POTENTIAL PRODUCTIVITY.

6.1 Introduction.

The potential productivity of forest land is a concept used to describe the maximum rate of production attainable by an area of land over a given period of time under the prevailing climatic conditions. In semi-natural forests potential productivity may be regarded as the maximum rates of productivity which occur naturally (Weetman 1983), but in managed forests the attainment of optimal edaphic conditions by cultivation and fertilising is usually assumed (Ford 1983).

The theory of potential productivity has largely been developed by crop ecologists (Ford 1983) and only relatively recently have attempts been made to apply these theories to forests (Jarvis 1981). The potential productivity of forest land has been reviewed by Jarvis (1981), Axelsson (1983) and Weetman (1983). Estimates of the potential productivity of forest land can be obtained either from theoretical consideration of tree assimilation processes or from forest growth data (Jarvis 1981). Problems arise in the first method due to inadequate knowledge of the quantities involved (Jarvis 1981) and in the latter due to the variety of possible quantities and time periods used to describe productivity (total dry weight, stem dry weight, volume ; period of maximum current annual increment, whole rotation).

It is apparent from previously published growth data that actual growth rates generally fall far short of potential growth rates. Jarvis (1981) estimated the mean annual and the maximum stem dry weight production of a selection of trees and agricultural crops from from various literature sources. The mean annual stemwood productivity of British conifers over a rotation length (in this case period up to age of maximum mean annual increment) was between 2 and 4 t ha^{-1} yr^{-1}, with maximum current annual increments of between 7 and 12 t ha^{-1} yr^{-1}. The average productivity levels of several agricultural crops in temperate zones were similar, being between about 2 and 8 t ha^{-1} yr^{-1}. The maximum productivity levels of coniferous crops are given as 20 - 50 t ha^{-1} yr^{-1} total dry weight production over short periods in the rotation. This is equivalent to about 13 - 33 t ha^{-1} yr^{-1} stemwood dry weight production, illustrating that actual productivity levels are considerably below potential. Ovington (1962) calculated a maximum net rate of current annual productivity for British conifers to be 22 t ha^{-1} yr^{-1}, with the mean rate for the entire rotation of 15 t ha^{-1} yr^{-1}. This is equivalent to about 17 and 12 t ha^{-1} yr^{-1} respectively for stem dry weight.

The value of potential productivity lies mainly in the fact that it can be used as a yardstick against which to assess actual productivity (Ford 1983). Reductions in productivity from a theoretical maximum can be studied in relation to various site conditions or crop treatments. Various such studies have been carried out for horticultural crops. For example Black (1964) described losses in the productivity of clover which were attributable to summer drought, inadequate leaf development in spring and excessive leaf development in autumn. From a practical point of view knowledge of the potential productivity of forest land could conceivably be used in land-use decisions and to resolve some of the long standing problems concerning the efficacy of various silvicultural treatments such as fertilising.

Fraser (1970) identified the highest GYC values recorded in Forestry Commission sample plots at various elevations, but no systematic attempt has been made in Britain to estimate the potential productivity of forest land under a range of climatic conditions. In the present study fairly good relationships have been demonstrated between productivity and the temperature conditions and wind-climate of upland sites. It was decided to try to estimate the maximum productivity level attained over a range of climatic conditions by identifying the plots showing the highest GYC values for specified conditions of climate (ie. specified temperature and wind conditions). This would then allow comparison between this theoretical maximum attainable level of productivity and those achieved in practice. The effects of various site factors could then be expressed in terms of their effect in reducing productivity from a theoretical maximum level. These reductions would be independent of the main climatic factors affecting productivity (temperature and windiness) but would be affected by all the other site and crop factors (particularly edaphic factors) known to influence productivity. Thus as well as being interesting in its own right, potential productivity also provides a means of segregating out the effects of the most important climatic factors from the remaining complex of site factors.

6.2 Calculation of "maximum attained yield class".

Any specific combination of values of accumulated temperature and tatter rate will be associated with a mean value of General Yield Class about which the observed values in the data will be distributed (in theory normally distributed) in a pattern determined largely by the effects of all the remaining site and crop factors. The aim of the analysis was to identify those data points which showed the maximum yield class values for specified conditions of estimated tatter rate and estimated accumulated temperature.

A two-way table was prepared in which the range of values of estimated tatter rate and estimated mean annual accumulated temperature were divided into suitable cells (Table 20). The following values were recorded for each cell:

1. The highest value of yield class.
2. The value of the residual for the data points in 1. above arrived at from a regression of GYC on estimated tatter rate and estimated accumulated temperature (ie. model 23 - see Table 9). This provides estimates of how far above the mean value of GYC these "maximum attained" values of GYC lie.

This table was used as the basis for selecting the plots which were thought to represent most closely the highest rates of productivity attainable over the range of climatic conditions encountered. No standard statistical procedure exists upon which to base such a selection process. It was not possible simply to choose those plots with the largest positive residuals (actual GYC - predicted mean GYC) because the residuals were apparently related to the GYC values, ie. decreasing values of GYC were associated with decreasing values of the residuals. The choice of plots was made so that each of the classes of GYC value 12-16, 16-20, 20-24, >24 was represented by at least 4 plots, the plots with the highest residual values being chosen. Only one plot was considered suitable to represent GYC values of 12 or less.

The relationships between productivity of these high yielding plots and tatter rate and temperature were then investigated using regression analysis, giving the following results:

Table 20. Values of maximum observed GYC and the corresponding residuals from model 26.

TATTER RATE CLASS (cm^2 day^{-1})	ACCUMULATED TEMPERATURE CLASS (day-degrees) 500	700	800	900	1000	1100	1200	1300
0	-	-	-	-	-	5.035*	-	-
	-	-	-	-	-	27.00	-	-
2	-	-	-	-	-	-	-	3.674*
	-	-	-	-	-	-	-	27.00
3	-	-	-	-	1.052	-	4.079*	-
	-	-	-	-	19.10	-	24.20	-
4	-	-	-	-	0.841	6.789*	-	-
	-	-	-	-	17.60	25.10	-	-
5	-	-	-	1.221	3.702*	3.158	-	-
	-	-	-	17.10	19.50	21.70	-	-
6	-	-	0.171	5.084*	6.108*	3.879*	0.928	-
	-	-	14.10	19.20	22.00	21.80	20.20	-
7	-	-	2.832	2.399	3.180	-	-	-
	-	-	16.00	16.60	18.60	-	-	-
8	-	1.986*	2.168*	3.316*	4.618*	5.293*	-	-
	-	12.70	13.70	17.00	19.20	22.20	-	-

CELL CONTENTS - residuals from model 23 (see Table 9)
- corresponding maximum observed GYC value

* OBSERVATIONS CHOSEN TO REPRESENT VALUES OF MAXIMUM ATTAINED GYC.

Table 20. (cont)

TATTER RATE CLASS (cm^2 day^{-1})	ACCUMULATED TEMPERATURE CLASS (day-degrees)							
	500	700	800	900	1000	1100	1200	1300
9	-	-	5.608*	3.069*	3.311*	-	1.791	-
	-	-	17.50	15.90	18.00	-	19.20	-
10	-	-	0.720	1.739*	-	0.973	-	-
	-	-	11.20	14.00	-	16.70	-	-
11	0.162	0.575	0.932*	-	3.943*	-	-	-
	6.30	10.30	11.90	-	17.20	-	-	-
12	-	-	0.686	-	-	-	-	-
	-	-	10.00	-	-	-	-	-

Maximum attained GYC = 7.50 − 0.942(tatter) + 0.0168(acc. temperature)

r^2 = 91.4% .... (58)

Maximum attained GYC = 10.2 − 0.0387(elevation) + 0.0398(topex)

− 0.802(tatter s.l.) + 0.0161(temperature s.l.)

r^2 = 92.1% .... (59)

The relatively high r^2 values are a reflection of the reduction in variation achieved by selecting the most highly productive sites. Productivity levels on such sites should be closely related to climatic factors and relatively independent of edaphic conditions which (at least in theory) should be optimal.

It should be emphasised that the values of maximum attained GYC do not exactly represent the maximum attainable productivity. This is because the data were taken from a pool of only 188 data points, none of which were chosen in the field specifically to represent potential growth rates. The plots chosen to represent the maximum attained level of productivity (19 in total) constitute 10% of the plots assessed. The productivity levels indicated by equations 58 and 59 above therefore represent the GYC values which one would expect to be exceeded with a frequency of 5 per cent.

Using the above equations, values of maximum attained GYC can be calculated for a range of climatic conditions. Figure 33 shows the values calculated for a range of elevations using equation 59 assuming the average values of topex, sea-level windiness and sea-level temperature encountered in this study. These values range from about GYC 32 at sea-level to GYC 6 at 650 m. This range of values is very similar to that quoted by Fraser (1970) arrived at by inspection of Forestry Commission sample plot data. A value of GYC of 32 is equivalent to a maximum mean annual dry weight increment of stemwood matter of 11.2 t ha^{-1} yr^{-1} (see Jarvis 1981), which is very close to the value of 12 quoted by Ovington (1962). The maximum elevation at which GYC 12 (the national average) can occur is predicted as about 500 m and the maximum for GYC 8 is a little over 600 m.

Values of GYC for Sitka spruce in southern Ireland frequently exceed 30 and values of between 36 and 40 have been recorded in young stands growing at about 100 m above sea-level (Davis 1982). Assuming a value for accumulated temperature at sea-level of 2100 day-degrees (Meteorological Office 1952) and

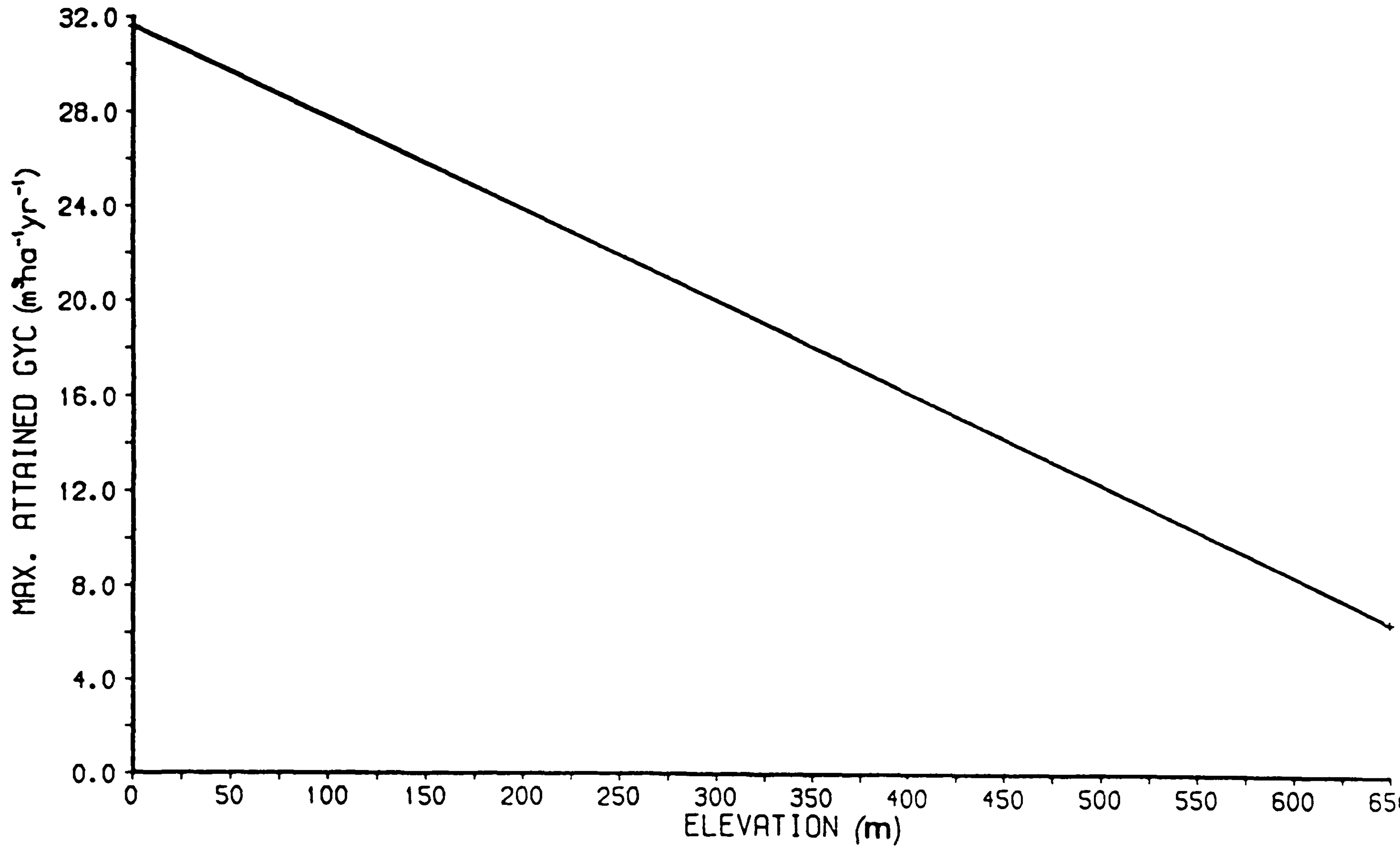


Figure 33. Relationship between maximum attained GYC and elevation for average site conditions in Scotland

wind conditions similar to the average for Scotland the maximum attained GYC for such a site predicted by equation 59 is 37.3 m^3 ha^{-1} yr^{-1}.

6.2.1 Comparison with subcompartment data-base values of GYC.

Values of maximum attained GYC were calculated from equation 59 for a range of elevations for two contrasting forests; Clatteringshaws (Galloway) and Drummond Hill (Perthshire). Clatteringshaws has a high proportion of peaty soils and is relatively exposed, whereas Drummond Hill is typified by mineral soils and a relatively sheltered location. Both had been relatively recently surveyed by the forest surveys branch of the Forestry Commission and data were available for the GYC and elevation of each subcompartment. Stands were selected which were at least 15 years old at the time of survey, so that the crops were old enough to allow reasonably precise estimation of yield class. Topex values are not recorded in the subcompartment data, so an average value was applied for each forest based on the authors knowledge of the areas (50 at Drummond Hill, 40 at Clatteringshaws).

Figures 34 and 35 show the values of GYC plotted against elevation and the calculated maximum attained GYC values. Taking into consideration the low precision of the subcompartment data and the fact that they are often subject to a degree of intentional under-estimation (G.M. Locke pers. comm.), the predicted values of maximum attained GYC appear to correspond reasonably well with the highest observed values of GYC. A considerable degree of variation in relationship between GYC and elevation is apparent, particularly at Clatteringshaws. Many of the subcompartments show values of GYC which lie far below the maximum theoretically attainable, indicating that site conditions other than temperature and windiness severely limit production. In the case of Clatteringshaws the preponderance of peat soils and *Calluna*-dominated sites at relatively low elevations probably contributes to this effect.

6.3 Comparison of actual and maximum attained GYC.

Values of maximum attained GYC were calculated for all the plots assessed in this study using equation 59, to give estimates of the potential productivity (ie. the maximum productivity attained under the prevailing climatic conditions). These values varied between GYC 8 and 30.

The ratio of actual GYC to maximum attained GYC was then calculated and

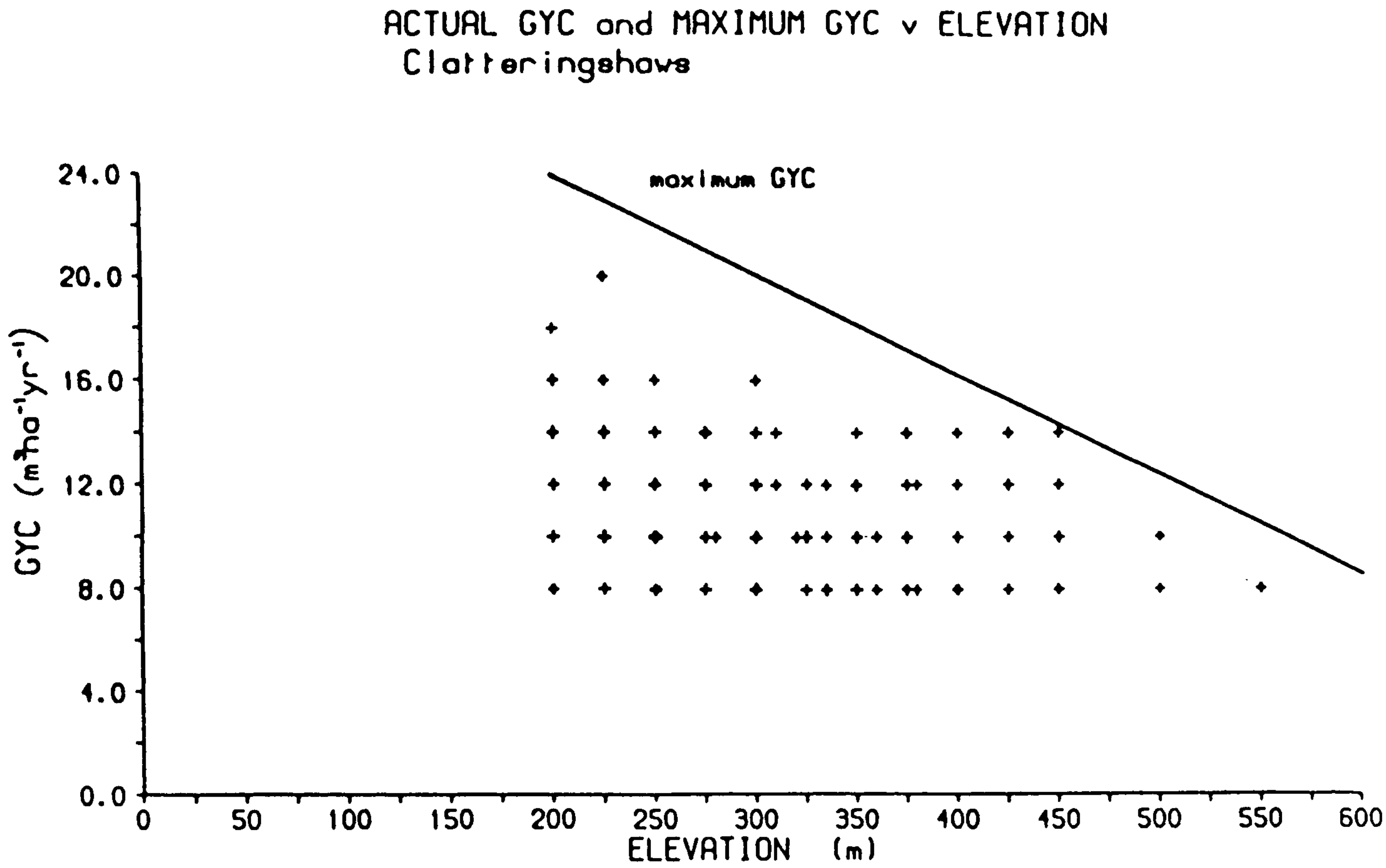


Figure 34. Comparison of predicted maximum GYC and observed GYC values at Drummond Hill forest (subcompartment data base)

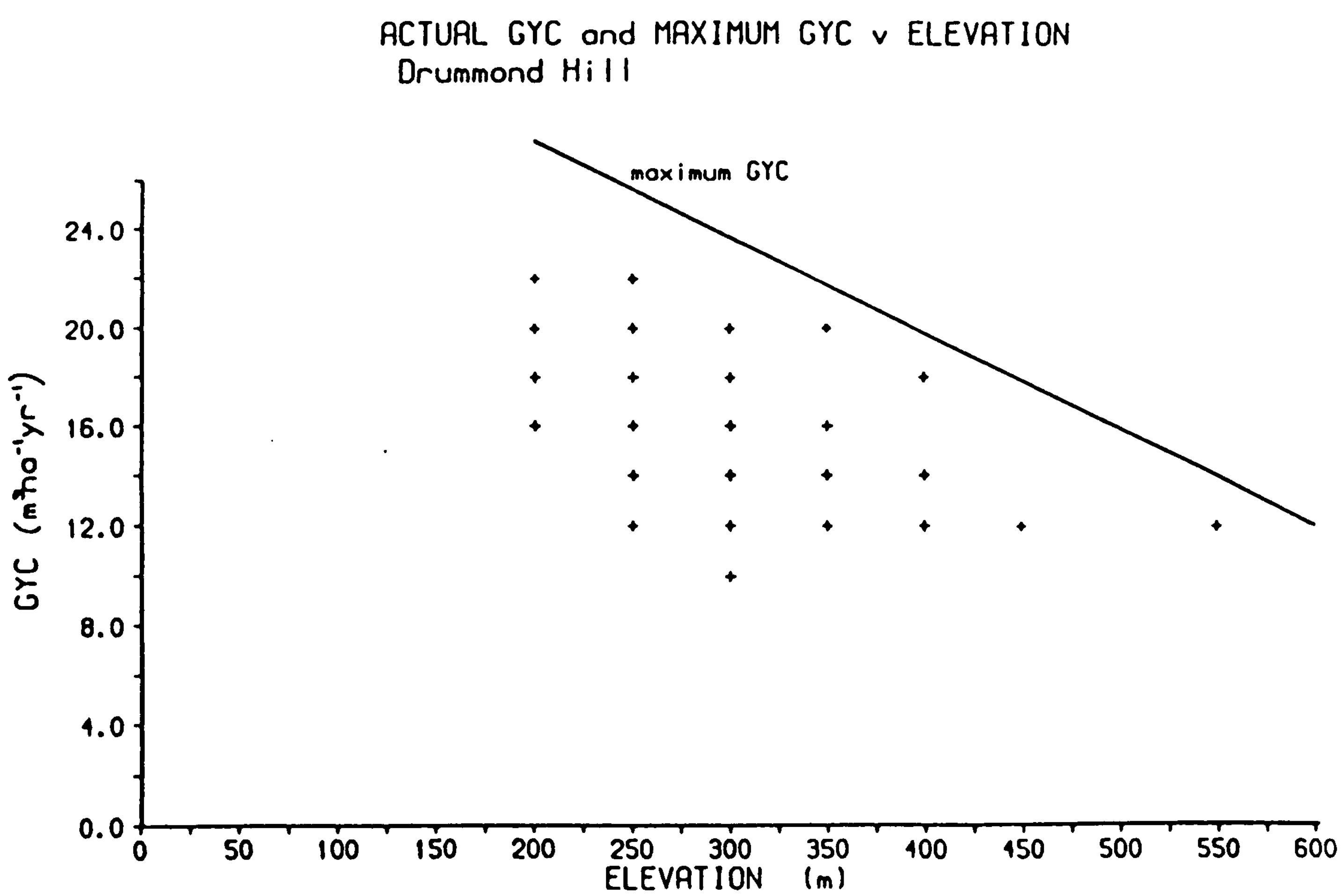


Figure 35. Comparison of predicted maximum GYC and observed GYC values at Clatteringshaws forest (subcompartment data base)

expressed as a percentage ("per cent maximum GYC"). This varied between 45 and about 100 per cent and was approximately normally distributed with a mean value of 80.4 per cent. (see Figure 36). The values in excess of 100 per cent were some of those used in the estimation of maximum attained GYC. These reductions in productivity from a theoretical maximum are presumably the result of the influence of environmental and crop factors other than temperature and windiness. The value of 80 per cent is fairly high and is probably a reflection of the fact that many of the crops surveyed only experience relatively low levels of nutrient stress and transient water stress.

Values of per cent maximum GYC were also calculated from the subcompartment data for Clatteringshaws and Drummond Hill forests. In both cases the values of per cent maximum GYC were more or less normally distributed, with a mean at Drummond Hill of 65 per cent and at Clatteringshaws of 55 per cent (see Figure 37). The generally lower values of per cent maximum GYC arrived at from the subcompartment data are probably a reflection of the rather less favourable sites (than those surveyed in the present study) and the fact that areas with unsuccessful silviculture are included. The conservative nature of GYC estimates in the subcompartment database may also contribute (G.M. Locke pers. comm.). As mentioned above the very low values of per cent maximum GYC recorded at Clatteringshaws presumably result from nutrient stress and heather check on the widespread peaty and *Calluna*-dominated sites.

6.3.1 Factors affecting "per cent maximum GYC".

The ratio of actual to maximum attainable productivity (per cent maximum GYC) should in theory be affected by a multiplicity of site factors other than those used to define the climate of the site for the purpose of calculating the potential productivity. For the data in this project per cent maximum GYC was found to be related to the following site factors: crop age, soil type and soil rooting depth. Details of these relationships are given below.

6.3.1.1 Crop age.

Values of per cent maximum GYC increased with decreasing crop age, crops younger than 20 years growing at 87 per cent of the theoretical maximum attained GYC and those older than 40 years growing at about 65 per cent (see Table 21 and Figure 38). The effect was significant ($P < 0.001$). This

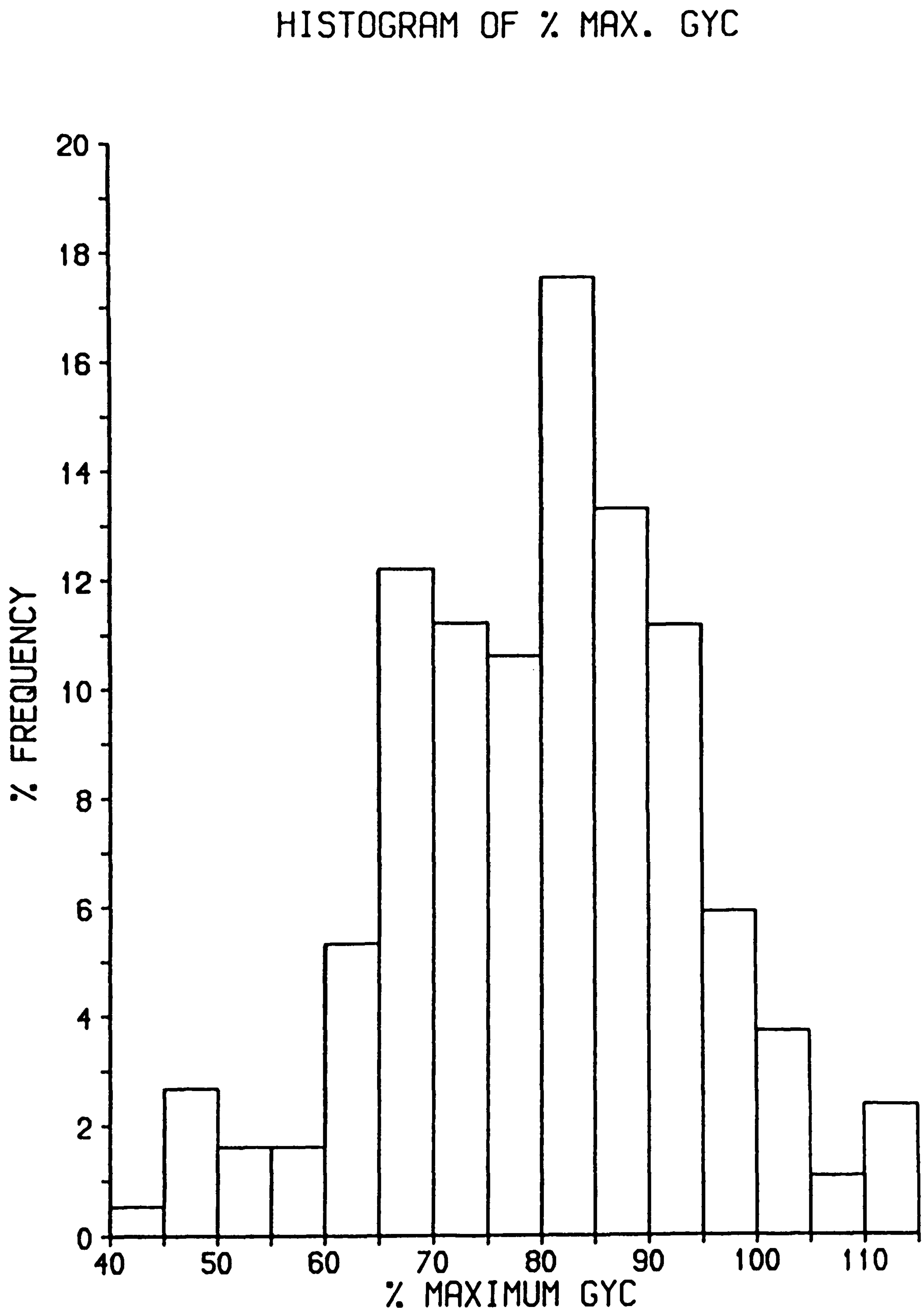
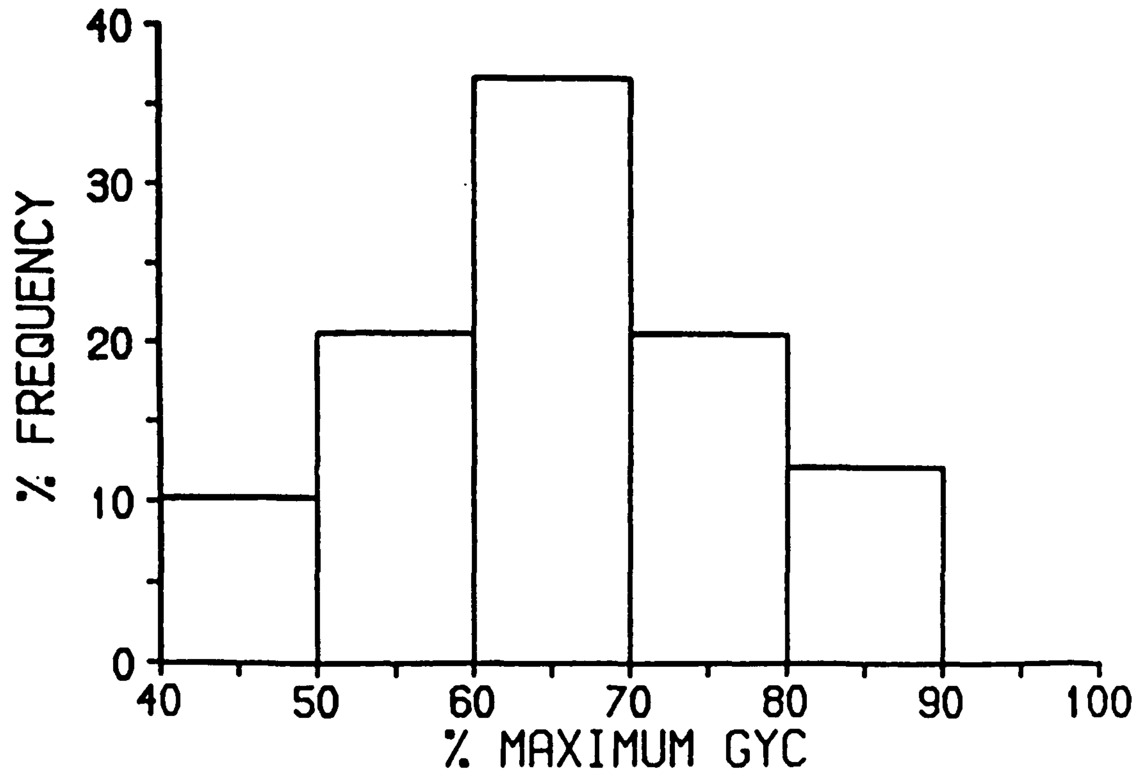


Figure 36. Histogram of per cent maximum GYC for the plots surveyed in this study

HISTOGRAM OF % MAX. GYC - Drummond Hill



HISTOGRAM OF % MAX. GYC - Clatteringshaws

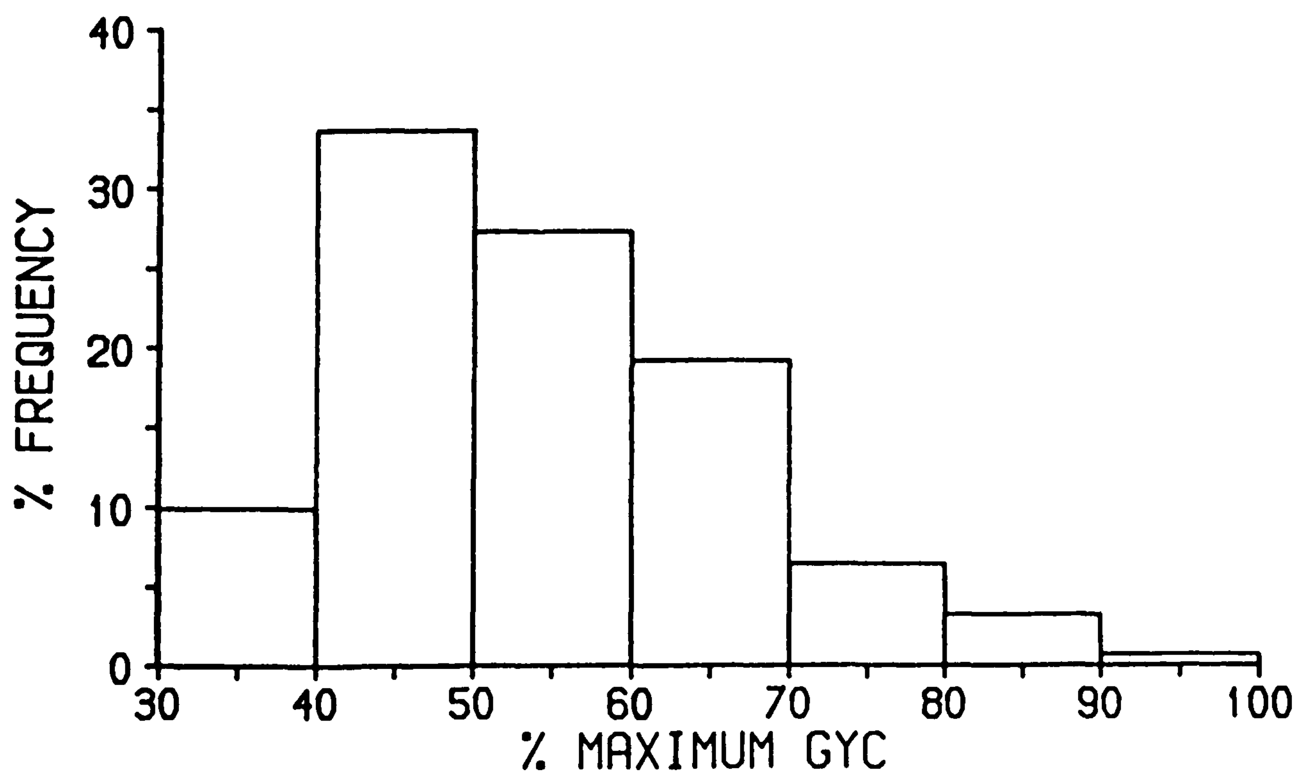


Figure 37. Histograms of per cent maximum GYC for Drummond Hill and Clatteringshaws forests

Table 21. Values of percent maximum GYC for different soil types and age classes of crop.

AGE CLASS	SOIL TYPE							
	BE	POD	IP	PG	SWG	FP	UP	ALL
	1	2	7	27	4	20	9	72
10-19	108.8	91.0	79.6	88.5	93.6	86.9	80.1	86.8
	-	2.47	6.52	8.28	7.72	10.74	11.82	9.94
	5	5	8	23	15	13	1	70
20-29	93.1	79.5	84.6	78.2	86.0	70.6	54.2	80.0
	3.03	17.52	15.67	11.83	12.75	8.95	-	13.60
	3	0	0	3	2	1	1	10
30-39	84.5	-	-	74.9	71.9	49.9	49.9	72.2
	3.15	-	-	8.28	7.86	-	-	13.68
	5	2	7	8	9	1	0	35
40+	71.8	67.5	72.6	62.7	72.1	61.7	-	69.7
	21.66	8.33	10.26	11.52	10.25	-	-	11.63
ALL	14	9	22	61	30	35	11	187*
	84.7	79.4	79.2	80.6	81.9	79.0	75.0	80.2
	16.87	15.09	13.07	13.17	13.42	13.76	15.52	13.70

CELL CONTENTS - number of observations
- value of % maximum GYC
- standard deviation

* excludes one value for skeletal soils.

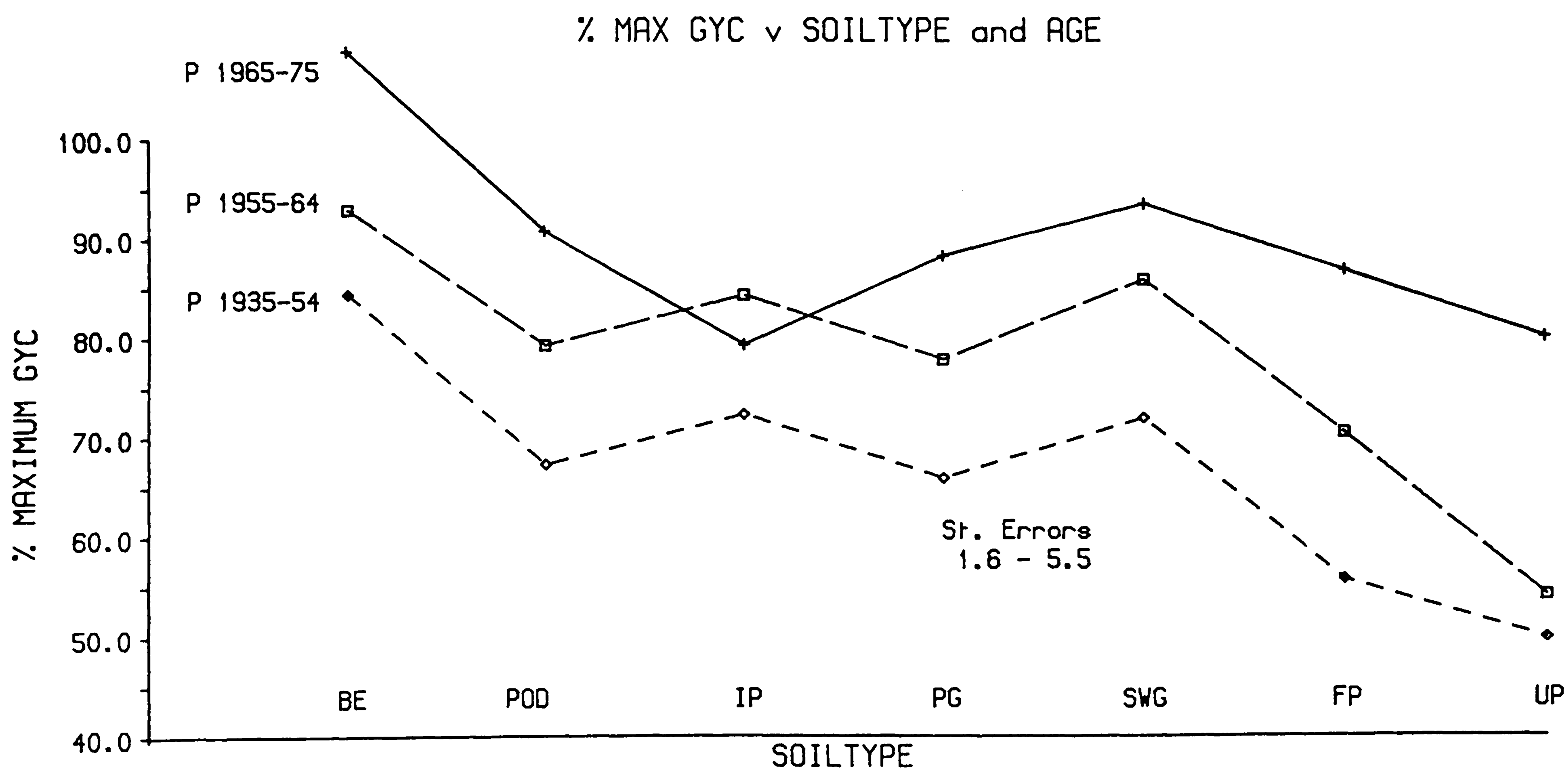


Figure 38. The effects of crop age and soil type on per cent maximum GYC

effect is similar to the significant effect of crop age demonstrated by regression analysis and is probably largely due to the increasing standards of silvicultural treatment applied to younger crops.

6.3.1.2 Soil type.

The effects of soil type on per cent maximum GYC are also shown in Table 21 and Figure 38. The soil types were generally found to order themselves in relation to productivity as follows: brown earth > surface water gley > podsol, iron pan, peaty gley > flushed peat > unflushed peat. The effect of soil type was significant at the 5% level. The absolute values for per cent maximum GYC for each soil type are largely dependent on the age class of the crop. These differences are similar to the significant effects of soil demonstrated by regression analysis (see section 5.3.3.2).

A comparison between the values of per cent maximum GYC for crops planted prior to 1955 and those planted after 1965 was made for the main soil groups (freely draining soils, gleys and peats). Most of the pre-1955 crops were established with a minimum of site amelioration whereas the post-1965 crop had all received modern silvicultural practice. In the pre-1955 crops the soil type classes ordered themselves as follows: freely draining 74 per cent, gleys 69 per cent and peats 54 per cent (see Figure 39 for significant differences). In the post-1965 crops the values of per cent maximum GYC had increased to 85-89 per cent (effect of age significant; $P < 0.001$) and the significant differences between soil types had disappeared. In the time period concerned peats showed an increase in per cent maximum GYC of 31 per cent, gleys of 20 per cent and freely drained soils of 12 per cent. This presumably reflects the influence of site amelioration which is aimed at removing the limitations to growth on poor sites, the greatest gains in terms of per cent maximum GYC being achieved on the poorest sites. The fact that peats have apparently "caught up" with the other main soil types in the youngest crops is rather surprising. This is possibly attributable to the fact that a substantial proportion of the data from young crops on peat soils come from Forestry Commission experiments which are suspected of showing slightly higher GYC values than standard plantations due to the rather greater degree of attention they receive during establishment.

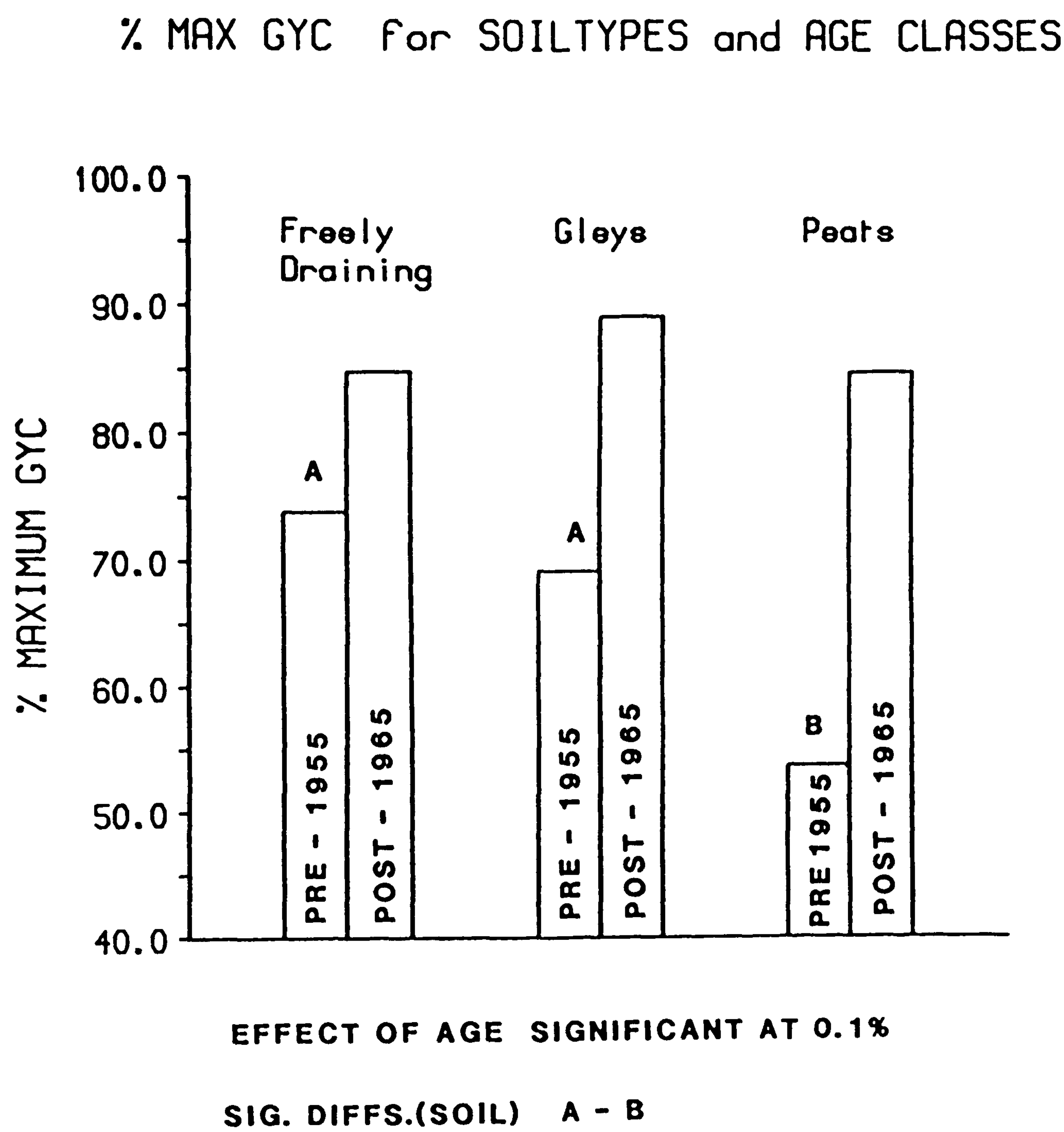


Figure 39. Comparison of per cent maximum GYC for different soil types for pre-1955 and post-1955 crops

6.3.1.3 Soil rooting depth.

The effects of soil rooting depth and total soil depth on per cent maximum GYC were investigated for the 167 plots for which values of soil depth were available. Regressions were calculated which included soil (total) depth, rooting depth, age and soil type.

Percent maximum GYC was significantly correlated with rooting depth, but the r^2 value was only 24 per cent. Percent maximum GYC was not correlated with total soil depth for the entire data set, but was if deep peats (which are associated with high values of total depth) were excluded (r^2 = 22%). In equations already containing crop age and soil type (as estimated by dummy variables), rooting depth and soil depth were not significantly related to per cent maximum GYC.

6.4 Conclusions.

1. Estimates of maximum attained productivity can be made by analysis of data from plots selected to represent the highest yielding crops sampled in this study. These maximum attained GYC values are closely related to the temperature and wind climate of the sites (r^2 = 91%). Under average climatic conditions in Scotland maximum attained GYC varies from about 32 near sea-level to about 6 at 650 m.

2. The values of maximum attained GYC predicted for lowland sites by the relationships between maximum attained GYC and climatic factors are very similar to published values of potential forest productivity for conifers in western Europe. This method of predicting maximum attained GYC also gives values which are reasonably consistent with maximum levels of productivity recorded for in the subcompartment data base for two Scottish forests (Clatteringshaws, Drummond Hill).

3. The actual productivity levels at the plots in this study lay between 45 and about 100 per cent of the calculated "maximum attained", with a mean value of about 80 per cent. Values arrived at by inspection of subcompartment data indicate that actual productivity in forest stands at Clatteringshaws and Drummond Hill was on average 55 per cent and 65 per cent of the calculated maximum attained.

4. The ratio actual/maximum attained GYC was affected by crop age, soil type and soil rooting depth.

CHAPTER 7

DISCUSSION AND CONCLUSIONS

7.1 Discussion.

7.1.1 The influence of climatic factors

This study is essentially an investigation of the relationships between site factors and productivity carried out based on old and well-tested methods and forms of analysis. One of its main features which distinguishes this investigation from previous British site-productivity studies is the reliance on extrapolated long-term meteorological data to describe key attributes of the climates of forest sites. These climatic data proved to be well correlated with productivity and these correlations formed the basis of all the models describing the relationships between site factors and yield. Another feature of this study is the use of dummy variables to establish the geographical distributions of variation in productivity and site wind-climate.

Previous studies of the relationships between forest productivity and site factors in Britain have relied to a large extent on topographic variables such as elevation and geomorphic position to describe the influence of climate (eg. Malcolm 1970, Page 1967, Cook et al. 1977) or have attempted to describe climate in terms of short-term measurements (Blyth 1974a). Using climatic variables rather than topographic factors brings the investigation a step nearer the biological processes governing growth, a move which seems to have been successful in this study. For example, in this study elevation accounted for 36 per cent of the variation in GYC. The addition of a variable describing the geographical variation in site wind-climate increased this figure (r^2) to 59 per cent and the further addition of a variable describing the geographical variation in site annual accumulated temperature increased it to 67 per cent. This move nearer to the biological processes made by using meteorological data is obviously a modest one seen in the context of physiologically orientated studies of plant-environment relationships. However in the case of this study it was essential for understanding and quantifying the pattern of spatial (ie. altitudinal and geographical) variation in productivity.

Demonstrating links between this pattern and site temperature and wind-climate is one of the most important results of this study. The existence of a pattern where productivity declines with increasing elevation and increasing proximity to the coast comes, of course, as no surprise to anyone, including foresters, with a knowledge of basic ecology. For example Burnett (1964) wrote in his standard text on Scottish vegetation:

> "In any area an altitudinal sequence of communities can usually be observed, but the absolute altitude at which any particular community occurs .... becomes progressively lower on going from south to north and west. The main causes ... appear to be 'oceanicity' and exposure".

Similarly the effects of oceanicity and latitude on treelines have been appreciated for nearly 100 years (Schröter 1912).

However, to be able to demonstrate and quantify these patterns using productivity data from 188 plots in Forestry Commission plantations is rather more surprising. Furthermore, the correlations between the pattern of variation in productivity and the distribution of variation in site temperature and windiness were rather closer than might have been expected considering the vast array of factors known to influence the growth of Sitka spruce. Temperature decreases rapidly with increasing latitude and modestly with increasing proximity to the coast (see Figures 13 and 14) whereas windiness increases rapidly with proximity to the coast and modestly with latitude (see Figure 15). Both patterns are correlated with the distribution of productivity, and all the "best" models derived in this study include these effects.

Forest site-yield studies are related to two other traditional forms of investigation into the relationships between environmental factors and plant performance namely:

1. Studies of the relationships between environmental factors and plant physiological processes.
2. Biogeographical studies of the relationships between environmental factors and plant attributes or species distribution.

The type of information required by foresters from site-yield studies lies between these two extremes. Some of the most interesting and challenging research carried out recently are studies which essentially attempt to link these approaches. For example Waring and co-workers, starting with the relationship between leaf area and basal area were able to show links between this measure and, on the one hand, patterns of carbon allocation within the tree and on the other the attributes and productivity of different forest communities in North America (Waring et al. 1978, Waring et al. 1980, Waring 1982).

It is probably true to say that traditional forest site-yield studies have not lived up to the expectation of many of the investigators in bridging the gap between knowledge of physiological plant processes and wider aspects of the attributes of forests including their productivity. One of the main problems with site-yield studies is that the complexity of the environmental system which affects forest tree growth to a large extent defies definition using multivariate statistics. In research into the relationships between environmental factors and plant growth at the physiological level this complexity is usually reduced by rationalising the environmental factors to their essential elements (temperature, light, moisture, nutrients) and studying their effects on a single or restricted number of plant processes in a controlled environment. This approach generally has the disadvantage of operating with environmental variables which are impractical to measure in the field, thus leaving their distribution in the forest uncharted.

Some of the most useful work on the relationships between site factors and yield has been done by concentrating on one important environmental variable and controlling or restricting the effects of other factors. For example Farr and Harris (1979) showed clear relationships between mean annual accumulated temperature above 5 °C and the site index of Sitka spruce by sampling over the whole latitudinal range (and climatic range) of the species in North America and choosing only productive stands up to an elevation of 100 m. Similarly, the effects of nutrients can be demonstrated by controlled experiments in which a wide range of fertilizer applications are applied to a single uniform site (eg. McIntosh 1985). In the present study the environmental factor which was concentrated on and around which the sampling strategy was designed was elevation, with its effects translated into climatic variables. In this respect the project built on the findings of previous studies (Page 1967, Malcolm 1970, Blyth 1974a). The amount of variation was restricted by selecting stands which were "silviculturally successful" and which had generally received a considerable degree of site amelioration treatment. The degree of variation was further reduced both intentionally and unintentionally by the choice of experimental sites (see section 7.1.6 below).

As a result of this approach it was possible to show the relationships between productivity and climatic factors and to show the spatial variability of these climatic factors, albeit in a fairly crude fashion. Even though the accuracy of the best models leaves a little to be desired when applied to a single site they are probably sufficiently precise to be of use in forest management. They certainly represent a very significant improvement on any other system currently available, with the possible exception of the "well-tuned local forester".

7.1.2 Tatter rate and accumulated temperature as a measure of exposure.

The combination of increasing windiness and decreasing temperature, both as a result of altitude and geographical location, provide a useful if rather crude definition of the word exposure. "Exposure" is a concept which means different things to different people and is a word which has been misused to a considerable extent in British forestry (see Grace 1977). "Exposed sites" are generally regarded as those where the climate is characterised by high mean wind speeds or high windrun, but the term is also used to describe sites with low levels of geomorphic shelter, more or less regardless of their actual wind-climate. The advent of the tatter (or "exposure") flag provided the Forestry Commission with a means of measuring this ill-defined quantity with a tool of dubious quality, an activity which was indulged in to a surprising extent as afforestation was pushed onto increasingly "exposed" sites. Analysis of the tatter flag data showed that "exposure" increased with increasing elevation and proximity to the sea and it was obvious to many people in the field that crop growth was related to exposure; whatever exposure might be. One major problem in relating the performance of tatter flags to crop growth was that the rate of tattering of flags was to a very large degree determined by site windiness (windrun) whereas it was an obvious over-simplification to assume that the same applied to the growth rates of trees. The effects of other factor such as temperature and soil type were therefore assumed to be correlated with site windiness.

In this study the author, rather to his surprise, came to rely to a large extent on tatter flag data to describe the wind-climate of sites, being, as it is, the only extensive source of data for upland areas. Decreasing growth of Sitka spruce was shown to be closely related to extrapolated values of tatter rate *and site temperature*. Estimated tatter rate and estimated accumulated temperature accounted for 78 per cent of the variation in GYC for plots having received standard silvicultural treatment. Exposure may therefore be considered as the combined effects of relatively high mean wind speeds and low growing season temperatures. However, the effects of more specific factors such as winter damage and foliage loss should not be overlooked and further research is needed to clarify their importance.

These results also indicate that the assessment of the suitability of sites for afforestation using tatter flags should be linked with a knowledge of the temperature regime of sites if even moderate levels of precision are required. This becomes obvious if one considers the contrast between a site in a west coastal area where the accepted limit to afforestation of 13 cm^2 day^{-1} is reached at elevations as low as 200 m and a site in the Cairngorms where the same limit is reached at 500 m or more. The temperature regimes of these site are completely different and so it is unrealistic to expect crops to behave similarly. Some recognition of this is now made by prescribing limits of 12 cm^2 day^{-1} for inland areas and 14 for coastal areas (Reynard and Low 1984). It is possible that this adjustment is not adequate. Further investigation of these effects could be simply carried out with reference of the results of this study.

One feature of the results of this study which contrasts strongly with the results of site-yield studies from many other parts of the world is the failure to demonstrate relationships between productivity and site moisture indices. This is despite the data being well separated according to rainfall estimates as shown by the results of principal component analysis (see section 5.4). It is possible that if this study had been extended onto lower elevation sites, a limiting effect of soil moisture might have become apparent. Soil moisture limitations may be the principal factor responsible for the fact that extrapolation of the relationships between productivity and site factors arrived at in this study tend to give consistent overestimations of productivity on low elevation sites. Jarvis et al. (1983) demonstrated relationships between the growth rate of Sitka spruce and evapotranspiration, and both Tranquillini (1979) and Oswald (1969) have reported productivity of conifers on altitudinal gradients reaching maxima at intermediate elevations below which productivity is limited by moisture supply.

7.1.3 The effects of edaphic factors.

In studies of the relationships between site and tree growth, it can be convenient to divide the features of the environment influencing growth into climatic and edaphic factors (Malcolm and Studholme 1972). In this study the effects of climatic factors dominated the effects of all other factors, including edaphic ones. This is in contrast to many North American studies where soil variables are often dominating (Carmean 1975), but is in agreement with most of the previous site/growth investigations carried out in Britain (Blyth 1974a). The clear dominance of climatic factors over edaphic ones is doubtless a true statement about plant-environment relationships in the British uplands, but this dominance is contributed to by several other factors. Firstly sampling was conducted over a very wide range of climatic conditions (both altitudinally and geographically), whereas the variation in soil factors was limited both unintentionally by the inevitable concentration of sampling on even valleyside sites and intentionally by avoiding from the start sites " with undue variation in soil conditions" (see section 2.3). In many of the North American studies climatic and topographic factors varied only to a modest degree and soil factors exerted a dominating influence. This illustrates the fact that conclusions drawn from site-yield studies are specific to the regions surveyed and are not general statements applicable to wider areas. Secondly the majority of plots were located in plantations which had received high levels of silvicultural inputs aimed specifically at removing edaphic limitations to productivity.

Although the effects of climate dominated, significant and useful relationships were found between productivity and soil type. The effects of soil type were treated by using dummy variables, thus overcoming the problems of interpreting the results based on *a priori* weightings which were encountered in many previous studies (Page 1970). Several practical methods of site classification applied in Great Britain have used soil type as a guide to forest productivity (eg. Pyatt 1977). This is because the distribution of soil types is to a certain extent correlated with climate and thus soil type is assumed to act as an integrating factor. The results of this study (bearing in mind possible shortcomings in the sampling strategy) allow a rational division of the effects of site factors influencing productivity into climatic and edaphic components.

7.1.4 The influence of crop age.

The existence of a significant negative relationships between productivity and crop age is interesting, and can be interpreted as the result of improving standards of silvicultural treatment. This apparent increase in GYC must be due to increased growth rates in the establishment phase. It is uncertain to what degree such "accelerated" growth will be maintained during the later life of crops. If it is not maintained, the values of GYC recorded for young crops in this study will be over-estimates, the discrepancy being greatest in the youngest crops. Study of the stability of GYC estimates with the age of crops has recently been carried out (Rollinson pers. comm.). The incidence of GYC estimates changing with age was found to be low and no specific trend was evident. However it remains to be seen to what degree these apparent gains in younger crops are maintained throughout their rotation length.

7.1.5 Potential productivity.

An estimate of potential site productivity was made by choosing the plots showing the highest rates of productivity for specific climatic conditions. This "maximum attained yield class" is an estimate of the maximum productivity attained given current silvicultural practices. It should be emphasised that rather higher levels of productivity could probably be recorded if data were collected specifically for the purpose of surveying maximum growth rates and particularly if Forestry Commission nutrition experiments were included in the sample. Despite this the estimates of "maximum GYC" made for low-level sites corresponded reasonably well with previously published data for western Europe (Ovington 1962, Jarvis 1981). The ratio of actual to potential productivity for the plots was surprisingly high (80 per cent), with actual productivity lying below potential by an average of 4 m^3 ha^{-1} yr^{-1} (average GYC in this study 14, average "potential" GYC 18). This is probably a reflection of the fact that many of the crops surveyed only experienced low levels of nutrient stress and only transient moisture stress.

Information on the potential productivity of a forest site could be used to identify crops whose productivity lies far below potential and to help to establish the causes of such shortfalls. It could also be used to give an indication of the likely benefit of silvicultural operations such as fertilizing. The method of estimating potential productivity presented here requires considerable refinement before it could be used in a practical context.

7.1.6 Some problems with the methodology of this study.

The degree to which the sites surveyed are representative of upland forest sites is not easy to assess. The sampling was definitely weighted in favour of even sloping valley-side sites with mineral soils (gleys), where a high standard of silviculture is easy to maintain. Flatter peaty sites and heathland sites were included as single plots or groups of plots often on Forestry Commission experimental sites. Many of these sites had also received a high standard of silvicultural treatment and it is uncertain whether such high standards would be applied in practice. Consequently predictions of productivity for "difficult sites" made using the models developed in this study may possibly tend to be overestimates unless high levels of silvicultural inputs are applied. This is particularly true of sites where *Calluna* dominates or in areas of unusual geology (eg. ultra-basic). In such areas the GYC values predicted by the models should be regarded as a guide to the productivity level which it is possible to attain given the prevailing climatic conditions.

The results of this study are based on plots which were "silviculturally successful". No attempt has been made to assess the degree by which the productivity of whole stands/compartments fall below this level due to irregularities in treatment. The limited comparisons made between the potential and actual productivity of subcompartments (section 6.3) indicate that these deviations may be significant, particularly on poor sites. With the exception of the poorest sites in this study it was felt that the plots gave a reasonable estimate of the productivity of the compartments within which they lay.

One of the main problems with the approach adopted concerns the accuracy of the extrapolated meteorological data. As mentioned in section 4.1.1.3, the errors associated with extrapolation include the effects of differences in site characteristics between the recording stations and the field sites, errors in the altitudinal (and other) functions used during extrapolation and errors in the spatial interpolation process which determines the pattern between stations. In addition the operation of tatter flags is associated with several hazards ranging from systematic errors due to the effects of rainfall (Grace 1977), to events such as the freezing of flags in winter. The main justification for the use of these extrapolated data is that they all show logical and consistent relationships with productivity. In the case of the tatter data the relationships between tatter rate and site variables are also logical and consistent. However more work remains to be done on the extrapolation of meteorological data to upland sites, particularly on the variability of lapse rates, the effects of aspect on site temperature and on assessing the reliability of tatter flag data.

7.2 Conclusions.

1. General Yield Class (GYC) decreased with increasing elevation due to the effects of increasingly adverse climatic and soil conditions. The relationships between GYC and elevation on the individual sites were fairly close (r^2 values 53-98 per cent) and were generally linear over the range of the elevations sampled, with GYC decreasing by an average of 3.5-4.0 m^3 ha^{-1} yr^{-1} per 100 m increase in elevation. There was some evidence of a tendency for the rate of decrease in GYC to be greater on high elevation (inland) sites than on lower elevation (coastal) sites.

2. The relationship between GYC and elevation varied according to geographical location. Covariance analysis showed that productivity at specific elevations was higher on inland and southern sites than on coastal and northern sites.

3. The geographical variation in the GYC/elevation relationship was closely correlated with patterns of growing season temperature and site windiness. Correlation and regression analyses showed that GYC was significantly correlated with the following climatic and topograhic variables: elevation, estimated mean summer temperature (June-Sept.), estimated mean annual accumulated temperature above 5.6 ^{o}C, estimated tatter rate (windiness), geomorphic shelter (topex), and aspect. The estimates of site temperature and windiness were derived by spatial and altitudinal extrapolation of standard meteorological data (temperature) and Forestry Commission tatter flag data (windiness). The best regression models containing the variables listed above accounted for 72-79 per cent of the variation in GYC.

4. The two variables, estimated tatter rate and estimated accumulated temperature, accounted for 78 per cent of the variation in GYC for 142 plots which had received standard silvicultural treatment. The combination of these

two variables provide a useful definition of the term "exposure" which combines the effect of increasing site windiness and decreasing site temperature.

5. Yield class was also significantly (negatively) related to crop age. This is regarded as a result of improved standards of silvicultural treatment during the period 1930 - 1970.

6. Soil type was significantly correlated with GYC, the different soil types ordering themselves with regard to productivity as follows: brown earth > surface water gley > podsol, iron pan, peaty gley > flushed peat > basin bog, unflushed peat. The amount of variation accounted for by soil factors was very small compared with climatic factors. This is probably the result of site amelioration practices which are aimed at reducing the effects of soil limitations on productivity.

7. The best regression models explained 78-86 per cent of the variation in GYC and their use to predict GYC for a single location (land acquisition) is associated with a mean error of approximately ±1 m^3 ha^{-1} yr^{-1} and confidence limits of ±2.3 - 2.6 m^3 ha^{-1} yr^{-1}. Comparison of the best models with validation data showed that the predictions of GYC for 32 single plots varied by on average ±1.48-1.67 m^3 ha^{-1} yr^{-1}, for the 9 individual forests varied by ±1.01-1.28 m^3 ha^{-1} yr^{-1} and the mean for all the plots differed from the true mean by + 0.02 to - 0.67 m^3 ha^{-1} yr^{-1}. These values compare with corresponding figures of about ±4.4 , ±2.6 and a mean error of - 4.1 m^3 ha^{-1} yr^{-1} for estimates derived from present site/yield guides published by the Forestry Commission (Busby 1974).

8. The best regression models could easily be adapted for yield prediction for forest management purposes. Information on the following site factors could be used to give reasonably precise estimates of the expected yield class given adequate silviculture: geographical location, elevation, topex score, aspect and soil type. Similarly, estimates of the elevations at which specific yield class values might be expected in different parts of northern Britain could also be made as an aid to determining upper planting limits.

9. The height to diameter ratio of the top-height trees on the plots was correlated with the windiness of the sites (tatter rate) and Production Class was correlated with elevation and stocking but the relationships were not

close. Variations in Production Class from plot to plot had a large random element due to variations in stocking and basal area growth. As a consequence Local Yield Class was only poorly correlated with site factors.

10. Estimates of the potential productivity of upland sites were made by analysis of data from plots showing the highest productivity for specific climatic conditions (as defined by site temperature and windiness). These "maximum attained yield class" estimates were closely related to temperature and windiness (r^2 = 91 per cent) and gave estimates for lowland sites similar to values of potential productivity quoted in the literature for western Europe. The ratio of actual to potential productivity varied according to crop age, soil type and rooting depth, actual productivity varying between about 45 and 100 per cent of potential with a mean value of 80 per cent.

7.3 Recommendations for future work.

1. The relationships between forest productivity and site conditions should be extended onto lower elevation sites. The meteorological variables used to describe the key attributes of the climate should include temperature, wind-climate and a measure of site water status.

2. Detailed studies of the relationships between climatic factors and the growth of coniferous trees at high elevations should be carried out using automatic weather stations at a limited number of sites spanning the range of climatic conditions encountered in the British uplands. These should be aimed at refining our knowledge of the mechanisms which cause reduced productivity and altered growth patterns at high elevations.

3. More information on the spatial distribution of the fundamental climatic variables in the British uplands is required. This will become increasingly important as more knowledge of the relationships between tree growth processes and meteorological variables becomes available from laboratory and single-site studies.

4. The collection of tatter flag data should continue and more work should be carried out on the relationships between site factors and tatter rate, particularly on sites with relatively high degrees of geomorphic shelter. It is essential that the flags cover a range of site conditions (topex values, aspects, elevation) at each site. The cover of flag sites in the dissected terrain in the

western Highlands should be increased. Studies of the variation in tatter rates over long time periods should be carried out and renewed efforts made to correlate tatter rates with mean wind speeds or windrun. The possible use of extrapolated tatter data to replace the scorings for windzone, elevation and topex in the windthrow hazard classification should be investigated.

5. Studies of the upper altitudinal limits of species other than Sitka spruce and including broadleaves should be carried out.

6. Studies of the potential productivity of tree species should be carried out using data collected specifically to illustrate maximum growth rates in various conditions of climate.

7. The relationship between productivity, windthrow hazard and site variables should be examined with the aim of assessing the likely losses due to premature felling on different sites. In this respect it should be noted that many of the site variables which appear in the best regression models in this study are also important in the windthrow hazard classification.

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APPENDICES

APPENDIX 1

SAMPLE PLOT DATA

Abbreviations in the following tables are as follows:

PLOT NO	Plot number
CON	Forestry Commission Conservancy
GRID REF	Grid references for upper and lower plots on transects, or for single plots
WZ	Wind zone
GYC	General Yield Class
ELE	Elevation (m)
ASP	Aspect
AS CL	Aspect class (1 = N 2 = NE etc 9 = valley bottom 10 = level hilltop)
TOP	Topex
RD	Rooting depth (cm)
TD	Total depth (cm)
N/h	Stocking per hectare
BA/ha	Basal area per ha (m^2)
BDH	Breast height diameter
H/D	Height to diameter ratio
TATT SL	Tatter rate adjusted to sea-level
TATT	Estimated tatter rate
ACC SL	Accumulated temperature adjusted to sea-level
ACC TEM	Estimated accumulated temperature
SUM SL	Summer temperature adjusted to sea-level
SUM TEM	Estimated summer temperature
PW	Potential water deficit class
OC	Oceanicity class
Codes:	S = standard silviculture P = production class assessed M = plot chosen to represent maximum attained GYC E = FC experiment T = actual tatter reading available
(ACT TATT)	Actual tatter rate value

PLOT NO	CON	DISTRICT	FOREST	GRID REF	W Z	GYC	ELE	ASP	AS CL	TOP	SL	SOIL TYPE	AGE	SOIL RD	TD
1	MS	COWAL	GLENBRANTER	NS113932	4	17.0	248	310	8	90	21	7L	25	75	99
2	MS	COWAL	GLENBRANTER		4	15.2	270	310	8	83	20	6L	25	65	90
3	MS	COWAL	GLENBRANTER		4	15.3	290	310	8	80	20	4BG	25	55	85
4	MS	COWAL	GLENBRANTER		4	14.3	311	312	8	74	19	3PG	25	61	90
5	MS	COWAL	GLENBRANTER		4	12.0	334	310	8	72	17	7L	25	50	80
6	MS	COWAL	GLENBRANTER		4	11.2	355	310	8	64	17	7L	25	60	90
7	MS	COWAL	GLENBRANTER		4	12.0	376	310	8	66	18	3P	22	45	83
8	MS	COWAL	GLENBRANTER		4	11.0	397	315	8	67	14	6L	22	45	70
9	MS	COWAL	GLENBRANTER		4	9.2	418	325	8	67	10	6L	22	38	70
10	MS	COWAL	GLENBRANTER	NS118929	4	8.7	440	310	8	72	12	6L	22	39	64
11	MS	KINTYRE	SOUTH KINTYRE	NR731326	2	7.9	335	321	8	17	8	11B	22	12	99
12	MS	KINTYRE	SOUTH KINTYRE		2	11.1	309	310	8	20	6	9E	22	10	99
13	MS	KINTYRE	SOUTH KINTYRE		2	11.9	286	288	7	29	7	9E	22	20	99
14	MS	KINTYRE	SOUTH KINTYRE		2	11.8	263	288	7	32	7	9	22	21	99
15	MS	KINTYRE	SOUTH KINTYRE		2	13.1	241	286	7	32	6	9	22	17	99
16	MS	KINTYRE	SOUTH KINTYRE		2	13.3	220	272	7	38	8	9	22	13	99
17	MS	KINTYRE	SOUTH KINTYRE		2	16.3	198	261	7	41	8	9	22	18	99
18	MS	KINTYRE	SOUTH KINTYRE		2	16.8	179	261	7	53	10	6LF	22	24	61
19	MS	KINTYRE	SOUTH KINTYRE	NR719324	2	20.2	158	252	7	68	12	6LF	22	22	70
20	MS	KINTYRE	SOUTH KINTYRE		2	11.1	322	318	8	20	7	9E	22	14	99
21	SS	CASTLE DOUGLAS	CLATTERINGSHAWS	NX502852	4	6.2	580	211	6	56	19	6L	20	32	40
22	SS	CASTLE DOUGLAS	CLATTERINGSHAWS		4	8.5	559	225	6	63	21	6L	20	41	61
23	SS	CASTLE DOUGLAS	CLATTERINGSHAWS		4	9.7	538	230	6	58	18	7L	20	42	50
24	SS	CASTLE DOUGLAS	CLATTERINGSHAWS		4	11.1	518	238	6	60	15	6L	21	25	85
25	SS	CASTLE DOUGLAS	CLATTERINGSHAWS		4	11.9	497	247	6	61	16	7L	21	36	55
26	SS	CASTLE DOUGLAS	CLATTERINGSHAWS		4	9.5	476	247	6	59	16	6LP	21	33	65
27	SS	CASTLE DOUGLAS	CLATTERINGSHAWS		4	13.0	455	256	7	64	10	6L	21	31	70
28	SS	CASTLE DOUGLAS	CLATTERINGSHAWS		4	14.9	433	236	6	68	12	6L	21	44	60
29	SS	CASTLE DOUGLAS	CLATTERINGSHAWS		4	14.0	412	214	6	71	13	7L	20	42	65
30	SS	CASTLE DOUGLAS	CLATTERINGSHAWS	NX496849	4	15.8	393	236	6	65	10	9	21	21	99
31	MS	ABERFOYLE	STRATHYRE 1	NN522228	5	11.8	531	63	3	89	16	7L	50	30	70
32	MS	ABERFOYLE	STRATHYRE 1		5	12.8	510	70	3	89	17	6L	50	60	99
33	MS	ABERFOYLE	STRATHYRE 1		5	14.1	486	72	3	90	18	7LF	50	39	70
34	MS	ABERFOYLE	STRATHYRE 1		5	14.5	446	68	3	85	14	4X	50	44	52
35	MS	ABERFOYLE	STRATHYRE 1		5	12.2	431	79	3	80	14	4PX	50	29	42
36	MS	ABERFOYLE	STRATHYRE 1		5	17.1	416	81	3	89	31	1U	50	54	74
37	MS	ABERFOYLE	STRATHYRE 1		5	17.6	393	103	3	97	23	4	50	70	75
38	MS	ABERFOYLE	STRATHYRE 1		5	17.5	370	94	3	105	13	4B	50	73	85
39	MS	ABERFOYLE	STRATHYRE 1	NN528321	5	15.8	338	65	3	112	9	7L	50	41	99
40	MS	ABERFOYLE	STRATHYRE 1		5	10.7	562	77	3	82	13	7L	50	52	62
41	SS	BORDER	WAUCHOPE	NY539988	4	18.0	308	270	7	24	4	6	19	28	86
42	SS	BORDER	WAUCHOPE	NY541987	4	19.2	331	266	7	25	7	6	19	39	82
43	SS	BORDER	WAUCHOPE	NY544987	4	14.6	375	267	7	28	8	7	19	36	50
44	SS	BORDER	WAUCHOPE	NY547987	4	13.4	421	251	7	19	6	3P	19	30	42
45	SS	BORDER	WAUCHOPE	NY548987	4	11.2	431	204	6	14	1	6P	19	30	70
46	SS	BORDER	WAUCHOPE	NT547012	4	15.6	379	263	7	29	8	7L	19	32	70
47	SS	BORDER	WAUCHOPE	NY549994	4	10.0	422	180	5	8	0	9	19	22	99
48	SS	BORDER	WAUCHOPE	NY546992	4	14.0	402	272	7	17	4	6P	19	32	76

PLOT NO	CON	DISTRICT	FOREST	GRID REF	W Z	GYC	ELE	ASP	AS CL	TOP	SL	SOIL TYPE	AGE	SOIL RO	SOIL TD
49	SS	BORDER	WAUCHOPE	NY546990	4	15.9	400	269	7	33	7	6PF	19	48	87
50	SS	BORDER	WAUCHOPE	NY549990	4	11.7	427	225	6	12	1	9	19	25	99
51	MS	TAY	DRUMMOND HILL	NN698431	5	19.1	355	145	4	69	20	1G	39	76	99
52	MS	TAY	DRUMMOND HILL		5	17.5	380	140	4	66	22	1	39	67	99
53	MS	TAY	DRUMMOND HILL		5	18.0	398	131	4	59	8	1G	39	53	74
54	MS	TAY	DRUMMOND HILL		5	15.2	421	130	4	58	15	7L	39	62	99
55	MS	TAY	DRUMMOND HILL		5	12.3	449	134	4	58	14	7L	39	76	80
56	MS	TAY	DRUMMOND HILL		5	16.0	478	144	4	58	19	1G	21	57	99
57	MS	TAY	DRUMMOND HILL		5	13.4	496	137	4	57	14	7L	21	58	85
58	MS	TAY	DRUMMOND HILL		5	14.0	515	135	4	57	16	7L	21	59	76
59	MS	TAY	DRUMMOND HILL		5	14.3	524	125	4	57	17	1U	21	52	86
60	MS	TAY	DRUMMOND HILL	NN695433	5	11.8	540	130	4	58	21	7L	21	60	99
61	SS	NITHSDALE	AE	NX994994	4	9.7	540	110	3	34	14	9	28	32	99
62	SS	NITHSDALE	AE		4	11.2	525	110	3	39	14	6LP	28	54	95
63	SS	NITHSDALE	AE		4	13.3	507	110	3	40	12	6L	28	54	95
64	SS	NITHSDALE	AE		4	15.2	490	110	3	42	9	7LF	28	78	99
65	SS	NITHSDALE	AE	NX993997	4	13.7	470	110	3	42	13	6LP	28	40	78
66	NS	WESTER ROSS	GLENSHIEL	NH033128	4	7.3	520	229	6	100	29	9	52	15	60
67	NS	WESTER ROSS	GLENSHIEL		4	7.9	500	229	6	102	38	6LP	52	66	99
68	NS	WESTER ROSS	GLENSHIEL		4	9.2	480	226	6	105	36	6L	52	48	90
69	NS	WESTER ROSS	GLENSHIEL		4	11.0	458	232	6	104	28	7L	52	55	65
70	NS	WESTER ROSS	GLENSHIEL	NH033126	4	12.0	435	230	6	106	20	4BP	52	50	65
71	NS	WESTER ROSS	RATAGAN	NG889212	2	21.1	260	42	2	82	19	7LF	26	49	99
72	NS	WESTER ROSS	RATAGAN		2	21.1	200	40	2	82	23	7LF	26	60	69
73	NS	WESTER ROSS	RATAGAN		2	24.2	140	41	2	82	25	1	26	78	99
74	NS	WESTER ROSS	RATAGAN		2	24.2	80	36	2	78	20	1	26	55	99
75	NS	WESTER ROSS	RATAGAN	NG896218	2	27.0	40	37	2	76	18	1G	26	50	60
76	MS	ARDGARTAN	CRIANLARICH	NN384243	5	21.7	231	350	1	47	8	6LP	18	31	62
77	MS	ARDGARTAN	CRIANLARICH		5	21.8	253	350	1	49	10	6L	19	46	70
78	MS	ARDGARTAN	CRIANLARICH		5	19.5	275	350	1	50	9	9F	19	31	70
79	MS	ARDGARTAN	CRIANLARICH		5	19.0	294	352	1	53	11	6L	19	35	70
80	MS	ARDGARTAN	CRIANLARICH		5	17.5	323	350	1	52	11	6L	18	25	51
81	MS	ARDGARTAN	CRIANLARICH		5	18.6	337	350	1	51	13	6L	19	31	49
82	MS	ARDGARTAN	CRIANLARICH		5	18.3	343	350	1	50	13	6LP	18	40	75
83	MS	ARDGARTAN	CRIANLARICH		5	15.2	381	353	1	55	15	9	19	25	99
84	MS	ARDGARTAN	CRIANLARICH		5	14.7	408	351	1	45	15	9	19	25	99
85	MS	ARDGARTAN	CRIANLARICH		5	14.0	422	340	1	61	14	6L	19	50	66
86	MS	ARDGARTAN	CRIANLARICH	NN388232	5	13.5	450	355	1	55	21	6LP	19	33	51
87	SS	AYRSHIRE	ARECLEOCH	NX168777	3	19.2	245	100	3	15	4	6LP	18	21	60
88	SS	AYRSHIRE	ARECLEOCH		3	16.6	265	104	3	15	4	9	18	31	99
89	SS	AYRSHIRE	ARECLEOCH		3	16.0	285	111	3	14	5	9	18	31	99
90	SS	AYRSHIRE	ARECLEOCH		3	16.5	305	101	3	14	4	6L	19	44	60
91	SS	AYRSHIRE	ARECLEOCH		3	15.7	315	103	3	15	0	9	19	24	90
92	SS	AYRSHIRE	ARECLEOCH		3	14.8	325	100	3	19	4	9	19	25	99
93	SS	AYRSHIRE	ARECLEOCH		3	13.2	345	92	3	18	4	9	19	15	99
94	SS	AYRSHIRE	ARECLEOCH	NX155782	3	13.7	365	100	3	25	10	6LP	19	39	60
95	SS	NEWTON STEWART	GLENTROOL	NX377829	3	11.8	198	270	7	31	0	11	33	16	99
96	SS	NEWTON STEWART	GLENTROOL	NX388835	3	10.4	274	270	7	34	10	9	33	22	99
97	SS	NEWTON STEWART	GLENTROOL	NX399829	3	7.0	451	280	7	43	10	9	21	18	66

PLOT NO	CON	DISTRICT	FOREST	GRID REF	WZ	GYC	ELE	ASP	AS CL	TOP	SL	SOIL TYPE	AGE	SOIL RO	TO
98	SS	NEWTON STEWART	GLENTROOL	NX363864	3	16.0	229	1	9	21	0	3	23	50	60
99	SS	NEWTON STEWART	GLENTROOL	NX373877	3	15.3	259	270	7	24	5	6LP	23	36	70
100	SS	NEWTON STEWART	GLENTROOL	NX310874	3	16.7	259	215	6	15	6	4B	28	43	99
101	SS	NEWTON STEWART	GLENTROOL	NX413897	3	17.2	366	160	5	23	6	7LF	25	40	99
102	SS	NEWTON STEWART	GLENTROOL	NX362901	3	22.2	256	1	9	31	0	7LF	18	50	99
103	MS	ABERFOYLE	STRATHYRE 2	NN537224	5	7.4	500	236	6	81	30	4B	49	49	52
104	MS	ABERFOYLE	STRATHYRE 2		5	11.0	475	236	6	82	29	4BP	49	50	99
105	MS	ABERFOYLE	STRATHYRE 2		5	11.3	450	240	6	89	29	3P	49	22	99
106	MS	ABERFOYLE	STRATHYRE 2	NN534223	5	13.5	425	240	6	92	26	3P	49	45	60
107	MS	ABERFOYLE	STRATHYRE 3	NN581178	5	7.9	540	272	7	47	24	6L	25	54	54
108	MS	ABERFOYLE	STRATHYRE 3		5	10.0	520	268	7	56	27	6LP	25	48	52
109	MS	ABERFOYLE	STRATHYRE 3		5	12.0	500	270	7	55	24	7L	25	54	69
110	MS	ABERFOYLE	STRATHYRE 3		5	14.0	480	270	7	61	25	7L	25	43	80
111	MS	ABERFOYLE	STRATHYRE 3	NN578178	5	19.2	460	273	7	90	16	3F	25	50	62
112	MS	LORNE	BALLACHULISH 1	NN052572	4	6.5	440	280	7	113	32	1U	53	45	55
113	MS	LORNE	BALLACHULISH 1		4	9.7	420	281	7	113	31	1U	53	55	55
114	MS	LORNE	BALLACHULISH 1		4	9.0	400	280	7	118	29	7L	53	44	66
115	MS	LORNE	BALLACHULISH 1		4	11.0	380	282	7	117	30	7L	53	47	72
116	MS	LORNE	BALLACHULISH 1		4	12.3	360	285	7	119	26	1G	53	60	70
117	MS	LORNE	BALLACHULISH 1	NN050573	4	14.2	340	285	7	120	21	7L	53	44	85
118	MS	LORNE	BALLACHULISH 2	NN039575	4	9.1	420	107	3	129	30	6LP	55	70	99
119	MS	LORNE	BALLACHULISH 2		4	11.9	395	105	3	128	34	13H	55	70	99
120	MS	LORNE	BALLACHULISH 2		4	13.9	370	101	3	127	33	13H	55	60	99
121	MS	LORNE	BALLACHULISH 2	NN041575	4	14.3	345	105	3	128	33	6L	55	50	54
122	NS	DORNOCH	SKIALL	NO019654	2	15.7	90	320	8	29	9	6L	35	40	40
123	NS	DORNOCH	HELMSDALE	NC883395	2	16.6	170	230	6	21	3	9	17	35	40
124	MS	FIFE	OCHIL	NN960035	5	25.1	350	335	8	88	20	1	15	40	65
125	MS	FIFE	OCHIL		5	20.0	390	335	8	84	20	6L	15	70	99
126	MS	FIFE	OCHIL		5	19.5	430	338	1	77	20	6LF	15	44	99
127	MS	FIFE	OCHIL		5	16.6	470	338	1	69	25	7LF	15	80	99
128	MS	FIFE	OCHIL		5	13.2	510	340	1	56	22	4BP	15	56	99
129	MS	FIFE	OCHIL	NN964031	5	11.0	540	338	1	49	25	6LP	15	55	99
130	MS	FIFE	OCHIL	NN968036	5	12.5	530	340	1	30	15	6LP	14	56	75
131	MS	FIFE	OCHIL	NN968038	5	14.5	457	340	1	19	15	6LP	14	58	60
132	MS	FIFE	OCHIL	NN949016	5	10.0	598	345	1	23	9	13H	18	52	99
133	MS	FIFE	OCHIL		5	9.0	570	340	1	50	20	4BP	18	45	45
134	MS	ANGUS	GLENPROSEN	NO237701	5	13.7	525	270	7	58	6	6LP	21	55	80
135	MS	ANGUS	GLENDOLL	NO287774	5	14.0	364	265	7	90	20	3	24	30	40
136	MS	ANGUS	GLENCLOVA	NO290774	5	11.9	470	265	7	75	15	6L	24	35	45
137	MS	COWAL	ARRAN	NR933308	3	17.7	200	250	7	24	10	6L	13	44	99
138	MS	COWAL	ARRAN		3	16.6	250	245	6	26	10	6LP	13	55	99
139	MS	COWAL	ARRAN		3	14.3	300	240	6	20	6	9C	13	39	60
140	MS	COWAL	ARRAN		3	10.8	350	225	6	25	13	6LP	13	43	80
141	MS	COWAL	ARRAN		3	9.6	400	230	6	20	4	9	13	60	85
142	MS	LOTHIAN&TWEED	GLENTRESS	NT287435	4	6.8	586	240	6	33	18	6P	31	30	99
143	MS	LOTHIAN&TWEED	GLENTRESS	NT287435	4	7.6	567	240	6	34	18	4	31	35	65
144	NS	DORNOCH	BORGIE	NC666539	2	13.8	177	270	7	12	7	6lp	16	25	71
145	NS	DORNOCH	BORGIE		2	13.0	148	290	7	7	6	9	26	28	48
146	NS	DORNOCH	BORGIE		2	15.5	128	290	7	28	6	6lp	35	38	58

PLOT NO	CON	DISTRICT	FOREST	GRID REF	W Z	GYC	ELE	ASP	AS CL	TOP	SL	SOIL TYPE	AGE	SOIL RO	TO
147	NS	DORNOCH	BORGIE		2	13.2	100	300	8	23	7	61	32	25	71
148	NS	DORNOCH	BORGIE		2	17.0	170	90	3	14	4	9	16	36	99
149	NS	DORNOCH	BORGIE		2	22.0	120	90	3	30	6	9	16	45	69
150	NS	STRONTIAN	SUNART	NM857734	3	11.3	325	225	6	121	35	13p	50	23	67
151	NS	STRONTIAN	SUNART		3	14.5	275	225	6	125	23	71	50	40	99
152	NS	STRONTIAN	SUNART		3	13.2	225	225	6	129	30	61	50	40	99
153	NS	STRONTIAN	SUNART		3	16.3	105	225	6	129	14	61	50	50	82
154	NS	STRONTIAN	SUNART		3	13.2	155	225	6	130	36	61	50	60	89
155	NS	BUCHAN	CLASHINDARROCH	NJ552327	5	10.4	412	1	10	4	5	4z	26	45	75
156	NS	BUCHAN	CLASHINDARROCH	NJ430308	5	11.4	412	0	1	34	15	9	24	50	82
157	NS	BUCHAN	CLASHINDARROCH	NJ427307	5	12.2	427	0	1	18	3	61	24	45	60
158	NS	BUCHAN	CLASHINDARROCH	NJ425316	5	10.8	412	1	10	16	0	4z	25	65	99
159	NS	BUCHAN	CLASHINDARROCH		5	17.5	408	180	5	26	10	4b	26	67	99
160	NS	BUCHAN	CLASHINDARROCH		5	10.0	473	180	5	16	10	4	26	48	99
161	NS	BUCHAN	CLASHINDARROCH		5	15.3	438	180	5	27	10	4b	26	30	45
162	NS	BUCHAN	FOREST OF DEER	NJ983582	2	16.2	140	23	2	6	3	61	17	55	99
163	NS	KINCARDINE	DRUMTOCHTY	NO697790	5	16.0	350	23	2	13	5	6z	17	33	48
164	NS	KINCARDINE	DRUMTOCHTY	NO696798	5	27.0	150	0	1	90	10	1	57	48	65
165	NS	DORNOCH	BALBLAIR 1p67	NH477954	4	13.8	305	22	1	16	9	10	15	48	63
166	NS	DORNOCH	BALBLAIR 2p67	NH477954	4	14.0	305	22	1	16	9	11	15	25	40
167	NS	BUCHAN	CLASHINDARROCH48	NJ426313	5	14.0	400	202	5	16	5	4b	15	99	99
168	NS	LOCHABER	CORROUR 1p71	NN412786	5	16.8	365	202	5	20	4	11	14	*	*
169	NS	BUCHAN	DEER 3p61	NJ893525	3	15.6	130	0	1	10	5	9	20	*	*
170	NS	KINCARDINE	DRUMTOCHTY 28p67	NO697785	5	16.1	350	90	3	13	7	3	16	*	*
171	NS	DORNOCH	HELMSDALE 2p68	NC896398	2	10.3	294	180	5	15	12	4px	15	*	*
172	NS	DORNOCH	LEWIS 1p69	NF845655	1	12.8	114	270	7	28	12	11	10	*	*
173	NS	DORNOCH	LEWIS 2p69	NF845655	1	13.8	53	45	2	24	11	11	10	*	*
174	NS	DORNOCH	LEWIS 3p69	NF845655	1	15.6	53	45	2	24	11	11	10	*	*
175	NS	DORNOCH	QUEENS 17p70	NJ009082	5	6.8	632	292	7	63	28	4z	15	*	*
176	NS	DORNOCH	QUEENS 18p70	NJ009082	5	7.8	632	292	7	63	28	4z	15	*	*
177	NS	SPEYSIDE	ROSARIE 2p70	NJ321492	5	16.0	320	1	10	14	7	4z	15	*	*
178	NS	DORNOCH	RUMSTER 3p68	NO166500	3	14.0	91	1	10	1	0	11	15	*	*
179	NS	DORNOCH	RUMSTER 5p71	NO084467	3	15.7	122	1	10	3	0	11	10	*	*
180	NS	DORNOCH	SHIN 19p69	NC600140	4	18.5	183	22	1	16	8	11	15	*	*
181	NS	DORNOCH	STRATHY 8p67	NC815596	2	16.8	106	90	3	13	11	9	15	*	*
182	NS	DORNOCH	TORRACHILTY 2P67	NM446676	5	6.3	600	315	8	57	31	11	15	*	*
183	NS	DORNOCH	TORRACHILTY 3p67	NM433690	5	12.7	413	315	8	41	16	9	16	*	*
184	SS	AYRSHIRE	ARECLEOCH 1p69	NX162779	5	16.0	280	135	4	15	5	11	14	*	*
185	SS	LOCKERBIE	WATERMEETINGS 1	NS966082	4	10.8	465	90	3	15	9	6	26	*	*
186	NEE	DURHAM	HAMSTERLEY 13p70	NY820443	5	9.2	650	157	5	10	7	9	10	*	*
187	NEE	DURHAM	HAMSTERLEY 14p70	NY820443	5	9.8	610	157	5	12	7	9	10	*	*
188	NEE	DURHAM	HAMSTERLEY 15p70	NY820443	5	8.3	650	157	5	10	7	9	10	*	*

PLOT No	N/h	BA/ ha	BDH	TOP HT.	H/O	TATT S.L.	TATT	ACC. S.L.	ACC TEM	SUM. S.L.	SUM. TEM.	RAIN FALL	P W	O C	CODE	(ACT) (TATT)
1	2050	44.05	13.2	22.7	58.24	7.5	5.41	1480	1101	13.7	12.2	2500	4	2	SP	
2	2750	39.59	12.1	20.3	59.40	7.5	6.37	1480	1070	13.7	12.0	2525	4	2	SP	
3	2150	43.19	12.1	22.4	53.97	7.5	6.94	1480	1043	13.7	11.9	2550	4	2	SP	
4	2650	42.56	11.5	20.8	55.29	7.5	7.62	1480	1015	13.7	11.8	2575	4	2	SP	
5	2300	31.76	10.0	18.7	53.40	7.5	8.29	1480	984	13.7	11.6	2600	4	2	SP	
6	2500	33.74	9.4	18.3	51.31	7.5	9.10	1480	957	13.7	11.5	2625	4	2	SP	
7	3250	27.98	8.5	15.2	55.72	7.5	9.48	1480	930	13.7	11.4	2650	4	2	SP	
8	2650	25.44	7.6	15.6	48.69	7.5	9.72	1480	903	13.7	11.3	2675	4	2	SP	
9	2950	14.72	6.6	13.0	51.04	7.5	10.12	1480	877	13.7	11.1	2700	4	2	SP	
10	2850	14.82	6.2	12.8	48.94	7.5	10.24	1480	850	13.7	11.0	2725	4	2	SP	
11	2200	11.91	5.6	12.2	45.39	9.0	13.15	1480	983	13.7	11.6	1780	3	1	SP	
12	2750	15.67	8.0	15.0	53.40	9.0	12.46	1510	1047	13.7	11.8	1760	3	1	SP	
13	1850	17.97	8.4	16.4	50.85	9.0	11.22	1510	1079	13.7	11.9	1740	3	1	SP	
14	3050	22.83	8.3	15.4	53.85	9.0	10.69	1510	1110	13.7	12.1	1720	3	1	SP	
15	2250	28.68	9.2	17.7	51.91	9.0	10.27	1510	1141	13.7	12.2	1700	3	1	S	
16	2100	24.88	9.3	19.6	47.33	9.0	9.49	1510	1171	13.7	12.3	1680	3	1	S	
17	3200	29.63	10.8	17.3	62.71	9.0	8.87	1510	1202	13.7	12.5	1660	3	1	SP	
18	3250	37.70	11.3	20.8	54.13	9.0	7.76	1510	1230	13.7	12.6	1640	3	1	SP	
19	3350	46.58	13.4	22.8	58.83	9.0	6.41	1510	1261	13.7	12.7	1620	3	1	SP	
20	2000	29.00	8.0	18.3	41.30	9.0	12.71	1510	1030	13.7	11.7	1770	3	1	SP	
21	3300	6.14	4.1	8.4	49.40	6.5	13.29	1580	791	13.8	10.3	2200	4	2	SP	
22	3300	20.52	5.4	12.7	43.96	6.5	12.45	1580	813	13.8	10.4	2180	4	2	SP	
23	2950	22.82	6.1	14.5	43.33	6.5	12.35	1580	837	13.8	10.5	2160	4	2	SP	
24	3000	26.68	7.2	15.4	47.17	6.5	11.84	1580	859	13.8	10.6	2140	4	2	SP	
25	3100	32.90	7.6	15.7	48.50	6.5	11.37	1580	883	13.8	10.8	2120	4	2	SPM	
26	3100	19.59	6.4	14.1	45.57	6.5	11.09	1580	907	13.8	10.9	2100	4	2	SP	
27	2850	31.02	8.4	17.9	46.76	6.5	9.80	1580	932	13.8	11.0	2080	4	2	SP	
28	2950	33.49	9.5	16.7	56.70	6.5	9.60	1580	959	13.8	11.2	2060	4	2	SP	
29	2800	32.85	8.9	18.0	49.40	6.5	9.11	1580	985	13.8	11.3	2040	4	2	SP	
30	3000	33.90	10.0	17.5	56.90	5.0	7.62	1580	1008	13.8	11.4	2020	4	2	SP	
31	1350	75.27	20.6	33.1	62.20	5.0	7.35	1580	844	13.8	10.6	2200	4	2		
32	1950	62.58	21.7	30.4	71.60	5.0	6.95	1580	868	13.8	10.7	2180	4	2		
33	1350	64.29	23.2	36.1	64.50	5.0	6.42	1580	896	13.8	10.8	2160	4	2		
34	1000	49.10	23.7	35.6	66.54	5.0	5.96	1580	943	13.8	11.1	2140	4	2		
35	1100	38.98	21.2	33.1	64.26	5.0	6.08	1580	961	13.8	11.2	2120	4	2		
36	1300	57.81	26.4	33.7	79.04	5.0	5.13	1580	980	13.8	11.3	2100	4	2		
37	700	62.22	26.7	43.6	61.35	5.0	4.29	1580	1008	13.8	11.4	2080	4	2		
38	600	53.59	26.7	38.3	69.64	5.0	3.24	1580	1037	13.8	11.5	2060	4	2		
39	950	69.10	24.7	41.1	60.22	5.0	2.29	1580	1079	13.8	11.7	2040	4	2		
40	1450	58.80	20.0	30.7	65.40	5.0	8.49	1580	810	13.8	10.4	2220	4	2		
41	4050	42.40	10.1	18.0	56.20	6.0	9.06	1510	1049	13.5	11.6	1500	3	2	SPTM	(7.4)
42	4600	44.98	10.8	17.7	56.79	5.0	8.44	1510	1018	13.5	11.5	1400	3	2	SPTM	(9.0)
43	3750	38.21	8.4	16.4	50.97	5.0	9.00	1510	961	13.5	11.2	1425	3	2	SPT	(8.9)
44	3550	30.91	7.7	16.1	47.79	5.0	10.55	1510	903	13.5	10.9	1460	3	2	SPT	(13.5)
45	3300	27.88	6.5	16.4	39.51	5.0	11.54	1510	891	13.5	10.9	1520	3	2	SPT	(12.4)
46	4400	48.10	8.9	18.2	48.90	5.0	9.02	1510	956	13.5	11.2	1520	3	2	SPT	(9.5)
47	4000	25.81	5.9	12.0	49.08	5.0	11.48	1510	902	13.5	10.9	1480	3	2	SPT	(11.8)
48	3650	34.14	8.1	18.0	44.60	5.0	10.21	1510	927	13.5	11.0	1520	3	2	SPTM	(10.9)
49	3450	34.56	9.0	17.7	50.82	5.0	9.27	1510	930	13.5	11.1	1500	3	2	SPTM	(7.7)

PLOT No	N/h	BA/ ha	BDH	TOP HT.	H/D	TATT S.L.	TATT	ACC. TEM.	ACC S.L.	SUM. TEM.	SUM. S.L.	RAIN FALL	P W	O C	CODE	(ACT) (TATT)
50	3200	34.18	6.8	16.1	42.36	5.0	11.59	1510	896	13.5	10.9	1520	3	2	SPT	(12.2)
51	850	55.82	23.1	37.9	61.05	3.0	3.79	1600	1077	13.7	11.5	1300	2	2	S	
52	550	40.24	22.2	34.5	64.55	3.0	4.46	1600	1045	13.7	11.4	1330	2	2	S	
53	950	47.68	22.4	31.7	70.63	3.0	5.15	1600	1022	13.7	11.3	1360	3	2	S	
54	2350	61.67	20.1	28.7	70.00	3.0	5.66	1600	993	13.7	11.1	1390	3	2		
55	2800	62.88	16.7	26.0	64.42	3.0	6.20	1600	959	13.7	11.0	1430	3	2		
56	5000	40.43	10.1	16.7	60.78	3.0	6.76	1600	925	13.7	10.8	1470	3	2	SP	
57	5350	49.45	8.7	15.4	56.23	3.0	7.17	1600	904	13.7	10.7	1500	3	2	SP	
58	3850	33.13	9.0	17.0	52.76	3.0	7.53	1600	882	13.7	10.6	1530	3	2	SP	
59	4050	35.59	9.2	18.6	49.70	3.0	7.71	1600	872	13.7	10.5	1560	3	2	SP	
60	5400	41.93	7.7	15.5	50.00	3.0	7.95	1600	854	13.7	10.4	1590	3	2	SP	
61	2150	35.01	9.8	22.4	43.97	5.0	10.96	1540	794	13.9	10.6	2100	4	2	SP	
62	3200	41.67	10.7	24.4	44.06	5.0	10.36	1540	811	13.9	10.7	2070	4	2	SP	
63	3500	65.71	12.6	26.2	47.94	5.0	9.95	1540	831	13.9	10.8	2040	4	2	SP	
64	2650	66.32	13.7	30.0	45.83	5.0	9.50	1540	851	13.9	10.9	2010	4	2	SP	
65	3750	50.12	12.7	25.4	50.06	5.0	9.11	1540	874	13.9	11.0	1990	4	2	SP	
66	2700	78.76	15.7	30.6	51.13	7.0	9.88	1450	727	13.1	9.9	3500	4	2	P	
67	2400	64.92	16.5	31.4	52.60	7.0	9.37	1450	750	13.1	10.1	3460	4	2	P	
68	2400	70.89	18.1	34.2	54.93	7.0	8.80	1450	773	13.1	10.2	3420	4	2	P	
69	3350	81.22	20.2	31.4	64.55	7.0	8.43	1450	799	13.1	10.3	3380	4	2	P	
70	2600	70.01	21.5	31.0	69.24	7.0	7.87	1450	826	13.1	10.4	3350	4	2	P	
71	1800	52.44	17.1	27.0	63.13	8.0	6.09	1440	1044	13.1	11.5	2200	3	2	SP	
72	2100	48.08	17.1	27.2	62.78	8.0	4.83	1440	1130	13.1	11.9	2150	3	2	SP	
73	3350	54.21	19.9	25.9	76.83	8.0	3.77	1440	1218	13.1	12.2	2100	3	2	SPM	
74	1800	43.76	19.8	33.4	59.40	8.0	2.86	1440	1311	13.1	12.6	2050	3	2	SP	
75	3050	52.53	20.6	25.5	80.56	8.0	2.12	1440	1374	13.1	12.8	2000	3	2	SPM	
76	3300	47.64	11.3	20.7	54.44	6.0	5.99	1550	1195	13.7	12.3	2320	4	2	SP	
77	3500	54.07	12.0	18.7	64.17	6.0	6.29	1550	1164	13.7	12.1	2340	4	2	SPM	
78	2550	38.68	10.9	21.4	50.60	6.0	6.55	1550	1134	13.7	12.0	2360	4	2	SP	
79	3250	41.27	10.7	18.0	44.86	6.0	6.73	1550	1108	13.7	11.9	2380	4	2	SP	
80	2250	17.70	9.3	17.1	54.68	6.0	7.35	1550	1069	13.7	11.7	2400	4	2	SP	
81	2100	26.61	10.5	18.3	57.49	6.0	7.78	1550	1050	13.7	11.6	2410	4	2	SP	
82	3300	31.39	9.6	17.7	54.46	6.0	7.86	1550	1042	13.7	11.6	2420	4	2	SP	
83	2500	28.71	8.7	16.8	51.75	6.0	8.38	1550	993	13.7	11.4	2450	4	2	SP	
84	2850	27.31	8.3	14.7	56.41	6.0	9.43	1550	960	13.7	11.2	2470	4	2	SP	
85	2050	31.36	7.8	17.2	45.34	6.0	8.70	1550	942	13.7	11.1	2490	4	2	SP	
86	2750	22.36	7.6	16.4	46.55	6.0	9.61	1550	908	13.7	11.0	2510	4	2	SP	
87	3500	39.20	10.1	21.3	47.42	7.6	9.06	1610	1235	13.7	12.2	1480	2	2	SP	
88	3200	44.56	8.6	18.3	46.99	7.6	9.44	1610	1207	13.7	12.1	1500	2	2	SP	
89	3350	38.81	8.5	16.3	52.14	7.6	9.99	1610	1180	13.7	11.9	1520	2	2	SP	
90	2350	34.42	9.4	18.6	50.53	7.6	10.28	1610	1153	13.7	11.8	1540	2	2	SP	
91	3800	31.93	8.9	16.3	54.60	7.6	10.41	1610	1139	13.7	11.8	1550	2	2	SP	
92	3650	41.57	8.5	17.6	48.30	7.6	10.35	1610	1126	13.7	11.7	1560	3	2	SP	
93	4200	37.27	7.5	14.9	50.33	7.6	10.80	1610	1100	13.7	11.6	1580	3	2	SP	
94	1800	22.66	7.9	16.9	46.75	7.6	10.75	1610	1074	13.7	11.5	1600	3	2	SP	
95	3450	45.78	13.7	19.3	70.98	7.0	7.40	1580	1272	13.8	12.6	1800	3	2	P	
96	3450	44.08	12.9	20.5	62.93	7.0	8.78	1580	1165	13.8	12.1	1830	3	2	P	
97	2700	8.92	4.6	8.7	52.87	7.0	11.53	1580	937	13.8	11.0	2100	4	2	S	
98	2850	38.29	11.5	22.0	52.27	7.0	8.88	1580	1228	13.8	12.4	1800	3	2	SP	(6.3)

PLOT No	N/h	BA/ ha	BDH	TOP HT.	H/D	TATT S.L.	TATT	ACC. T.L.	ACC TEM	SUM. S.L.	SUM. TEM.	RAIN FALL	P W	O C	CODE	(ACT) (TATT)
99	3000	43.23	11.1	22.6	49.11	7.0	9.01	1580	1186	13.8	12.2	1850	3	2	SP	
100	2850		12.9	23.2	55.60	7.0	10.16	1580	1186	13.8	12.2	1800	3	2	S	
101	3200	47.97	13.5	22.7	59.47	7.0	11.46	1580	1043	13.8	11.6	1850	3	2	SPM	(9.6)
102	2900	41.92	11.5	20.0	57.75	7.0	8.78	1580	1190	13.8	12.2	1830	3	2	SPM	
103	3344	61.77	15.1	32.4	46.76	5.0	8.68	1580	880	13.8	10.8	2180	4	2	P	
104	2926	63.32	19.2	30.4	63.32	5.0	8.14	1580	909	13.8	10.9	2160	4	2	P	
105	*	*	19.7	27.9	70.48	5.0	7.22	1580	938	13.8	11.1	2140	4	2		
106	*	*	22.2	34.6	64.43	5.0	6.55	1580	969	13.8	11.2	2120	4	2		
107	2350	31.63	7.1	18.7	37.87	5.0	11.00	1580	834	13.8	10.5	2400	4	2	SP	
108	*	*	8.7	18.9	45.90	5.0	10.15	1580	857	13.8	10.6	2375	4	2	S	
109	2500	48.29	10.0	22.8	44.08	5.0	9.73	1580	880	13.8	10.8	2350	4	2	SP	
110	*	*	11.3	18.6	60.85	5.0	9.07	1580	903	13.8	10.9	2325	4	2	S	
111	2050	61.73	15.0	24.3	61.73	5.0	6.87	1580	926	13.8	11.0	2300	4	2	SPM	
112	2950	70.57	14.8	29.2	50.68	8.0	8.04	1470	840	13.2	10.5	2800	4	2	P	
113	2600	66.70	19.1	32.4	58.95	8.0	7.66	1470	865	13.2	10.6	2780	4	2	P	
114	3200	70.21	18.4	29.9	61.53	8.0	6.96	1470	890	13.2	10.8	2760	4	2	P	
115	2750	83.10	20.6	34.5	59.70	8.0	6.64	1470	915	13.2	10.9	2740	4	2	P	
116	*	*	22.3	40.1	55.74	8.0	6.13	1470	940	13.2	11.0	2720	4	2		
117	*	*	24.1	40.0	60.37	8.0	5.68	1470	966	13.2	11.1	2700	4	2		
118	2500	56.54	18.4	32.4	56.54	8.0	5.71	1470	865	13.2	10.6	2800	4	2	P	
119	*	*	22.3	34.0	65.56	8.0	5.39	1470	896	13.2	10.8	2770	4	2		
120	*	*	24.5	30.4	81.08	8.0	4.97	1470	927	13.2	10.9	2750	4	2		
121	*	*	24.7	41.3	59.80	8.0	4.32	1470	960	13.2	11.1	2725	4	2		
122	5450	99.99	18.2	29.1	62.43	9.0	7.77	1190	1045	12.3	11.7	900	1	1	P	
123	2250	25.90	7.8	14.9	52.34	7.8	8.86	1240	973	12.4	11.3	1100	3	2	SP	
124	*	*	10.1	16.6	60.66	4.0	4.00	1620	1103	13.8	11.7	1600	3	2	SM	
125	*	*	8.2	11.2	73.21	4.0	5.02	1620	1052	13.8	11.4	1630	3	2	S	
126	*	*	8.0	14.8	54.39	4.0	5.85	1620	1002	13.8	11.2	1660	3	2	SM	
127	*	*	6.8	14.0	48.92	4.0	7.12	1620	954	13.8	10.9	1690	3	2	S	
128	*	*	5.4	15.1	35.76	4.0	8.71	1620	908	13.8	10.7	1720	3	2	S	
129	*	*	4.3	10.1	43.28	4.0	9.72	1620	874	13.8	10.5	1750	3	2	S	
130	2350	9.91	4.6	11.2	41.52	4.0	10.72	1620	885	13.8	10.6	1750	3	2	ST	(13.7)
131	2550	15.37	5.5	13.5	40.59	4.0	9.90	1620	970	13.8	11.0	1690	3	2	ST	(10.9)
132	*	*	5.4	11.7	45.73	4.0	12.47	1620	812	13.8	10.2	1790	3	2	ST	(13.7)
133	*	*	4.8	11.3	42.48	4.0	10.24	1620	841	13.8	10.3	1760	3	2	S	
134	*	*	8.8	16.5	53.64	3.2	8.22	1530	801	13.5	10.3	1400	3	3	STM	(7.2)
135	4000	30.12	10.7	18.0	59.44	3.2	3.22	1510	975	13.4	11.2	1500	3	3	SP	
136	3900	47.83	9.3	18.6	50.27	3.2	6.10	1510	844	13.4	10.5	1550	3	3	SP	
137	*	*	5.9	14.0	42.14	8.0	8.98	1560	1250	13.6	12.4	1600	2	1	S	
138	*	*	5.6	13.7	40.73	8.0	10.20	1560	1178	13.6	12.1	1650	3	1	S	
139	*	*	4.8	9.8	49.49	8.0	11.64	1560	1110	13.6	11.8	1700	3	1	S	
140	*	*	3.5	8.0	43.75	8.0	12.29	1560	1043	13.6	11.5	1750	3	1	S	
141	*	*	2.6	5.5	47.27	8.0	13.57	1560	980	13.6	11.2	1800	3	1	S	
142	*	*	4.4	8.6	51.16	5.1	13.44	1500	704	13.6	10.0	1100	3	3	S	
143	*	*	5.1	11.3	44.49	5.1	12.91	1500	725	13.6	10.1	1100	3	3	S	
144	2550	16.30	6.3	13.0	48.46	8.8	10.08	1240	963	12.3	11.2	1100	2	2	SPT	(9.8)
145	1900	42.88	11.3	22.9	49.34	8.8	9.83	1240	1006	12.3	11.4	1080	2	2	P	
146	3350	65.56	17.9	28.5	62.81	8.8	8.14	1240	1036	12.3	11.5	1060	2	2	P	
147	3150	57.88	14.5	22.9	63.31	8.8	8.04	1240	1080	12.3	11.7	1050	2	2	P	

PLOT No	N/h	BA/ ha	BOH	TOP HT.	H/D	TATT S.L.	TATT	ACC. TEM.	ACC S.L.	SUM. TEM.	SUM. S.L.	RAIN FALL	P W	O C	CODE	(ACT) (TATT)
148	2350	24.37	7.7	15.3	57.04	8.8	8.87	1240	973	12.3	11.2	1100	2	2	SPM	
149	3000	30.65	9.8	17.2	56.81	8.8	6.91	1240	1049	12.3	11.5	1060	2	2	SPM	
150	2950	63.30	20.1	28.4	70.77	7.0	4.81	1450	966	13.1	11.1	3180	4	2	P	
151	3800	85.50	23.6	32.6	72.39	7.0	3.69	1450	1034	13.1	11.4	3150	4	2	P	
152	3150	74.42	22.2	29.6	74.87	7.0	2.48	1450	1104	13.1	11.7	3120	4	2	P	
153	2850	80.49	25.6	34.3	74.55	7.0	0.16	1450	1282	13.1	12.4	3060	4	2	P	
154	*	*	22.2	28.3	78.44	7.0	1.06	1450	1206	13.1	12.1	3090	4	2	P	
155	*	*	9.4	16.1	58.38	4.3	10.78	1460	865	13.3	10.8	900	2	3	T	(11.8)
156	*	*	11.4	20.9	54.55	4.3	8.59	1460	865	13.3	10.8	1200	2	3		
157	*	*	9.6	15.2	63.15	4.3	9.78	1460	846	13.3	10.7	1200	2	3	ST	(8.3)
158	*	*	9.0	12.3	73.17	4.3	10.03	1460	865	13.3	10.8	1200	2	3		(9.3)
159	*	*	14.2	22.9	62.30	4.3	9.38	1460	870	13.3	10.8	1200	2	3	M	
160	*	*	9.1	18.0	50.55	4.3	11.16	1460	791	13.3	10.4	1200	2	3		
161	*	*	12.6	21.4	58.89	4.3	9.80	1460	833	13.3	10.6	1220	2	3		
162	*	*	7.8	12.4	62.90	8.9	9.32	1400	1178	12.9	12.0	920	1	2	S	
163	*	*	7.3	11.2	65.17	3.4	7.44	1400	883	13.2	11.1	1000	2	2	ST	(7.4)
164	*	*	37.5	57.7	64.99	3.4	0.00	1400	1163	13.2	12.3	950	2	2	SM	
165	*	*	*	*	*	5.1	8.35	1290	833	12.7	10.8	1300	3	2	STE	(8.0)
166	*	*	*	*	*	5.1	8.35	1290	833	12.7	10.8	1300	3	2	STE	(8.0)
167	*	*	*	*	*	3.4	8.86	1460	880	13.3	10.9	1220	2	3	STE	(9.3)
168	*	*	*	*	*	5.0	9.53	1460	924	13.3	11.1	1700	4	2	SE	
169	*	*	*	*	*	8.9	9.15	1410	1203	12.9	12.1	920	1	2	STE	
170	*	*	*	*	*	3.4	7.01	1420	903	13.3	11.2	1000	1	2	STE	(7.4)
171	*	*	*	*	*	7.8	11.37	1240	798	12.3	10.5	1080	3	2	STE	(11.1)
172	*	*	*	*	*	11.7	10.77	1330	1148	12.7	12.0	1350	2	1	STE	(10.8)
173	*	*	*	*	*	11.7	9.32	1330	1243	12.7	12.3	1350	2	1	STE	(9.0)
174	*	*	*	*	*	11.7	9.32	1330	1243	12.7	12.3	1350	2	1	STE	(9.0)
175	*	*	*	*	*	3.5	10.38	1480	636	13.5	9.7	1300	3	3	STE	(10.0)
176	*	*	*	*	*	3.5	10.38	1480	636	13.5	9.7	1300	3	3	STE	(10.0)
177	*	*	*	*	*	3.5	7.58	1480	1003	13.4	11.4	1000	2	3	SE	
178	*	*	*	*	*	8.5	8.97	1210	1063	12.2	11.6	920	2	2	STE	(6.4)
179	*	*	*	*	*	8.5	9.44	1210	1016	12.2	11.4	920	2	2	SE	
180	*	*	*	*	*	5.0	5.90	1300	1014	12.6	11.5	1100	2	2	SE	(5.4)
181	*	*	*	*	*	9.1	8.00	1200	1030	12.3	11.6	1030	2	2	SE	(8.9)
182	*	*	*	*	*	4.8	11.56	1370	560	13.1	9.5	1400	3	2	STE	(10.7)
183	*	*	*	*	*	4.8	8.95	1370	773	13.1	10.6	1300	3	2	STEM	(9.8)
184	*	*	*	*	*	7.6	10.22	1610	1187	13.7	12.0	1520	2	2	SE	
185	*	*	*	*	*	4.9	10.50	1500	840	13.8	11.0	1800	3	2	SE	
186	*	*	*	*	*	3.7	14.36	1640	778	14.2	10.3	1450	3	3	STE	(14.4)
187	*	*	*	*	*	3.7	13.46	1640	819	14.2	10.5	1450	3	3	STE	(13.7)
188	*	*	*	*	*	3.7	14.36	1640	778	14.2	10.3	1450	3	3	STE	(14.4)

APPENDIX 2a

REGRESSION ANALYSIS FOR MODEL 2

The regression equation is

C3 = 27.3 - 0.0428 ELEVATION - 3.21 C5 + 4.96 C6 + 5.77 C7 + 3.73 C8 + 7.35 C9
+ 6.99 C10 + 2.66 C11 + 2.37 C12 + 4.77 C13 + 1.51 C14 + 0.445 C15
+ 8.57 C16 - 0.669 C17 - 4.32 C18

Predictor	Coef	Stdev	t-ratio	
Constant	27.3123	0.9494	28.77	
ELEVATION	-0.042810	0.002349	-18.22	
C5	-3.2128	0.7382	-4.35	SOUTH KINTYRE
C6	4.9576	0.7804	6.35	CLATTERINGSHAWS
C7	5.7687	0.6785	8.50	STRATHYRE
C8	3.7264	0.7134	5.22	WAUCHOPE
C9	7.3519	0.7525	9.77	DRUMMOND HILL
C10	6.9866	0.9444	7.40	AE
C11	2.6565	0.9199	2.89	GLENSHIEL
C12	2.3723	0.9832	2.41	RATAGAN
C13	4.7717	0.6892	6.92	CRIANLARICH
C14	1.5107	0.7533	2.01	ARECLEOCH
C15	0.4451	0.7125	0.62	BALLACHULISH
C16	8.5691	0.7788	11.00	OCHIL
C17	-0.6694	0.8699	-0.77	ARRAN
C18	-4.3226	0.9138	-4.73	SUNART

s = 1.577   R-sq = 85.9%   R-sq(adj) = 84.0%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	15	1766.76	117.78
Error	117	290.98	2.49
Total	132	2057.75	

SOURCE	DF	SEQ SS	
ELEVATION	1	806.12	
C5	1	161.09	TOTAL SS FOR SITES :
C6	1	1.38	= 959.79
C7	1	15.54	
C8	1	0.67	F-RATIO FOR SITES :
C9	1	96.09	= 68.56/2.49
C10	1	32.40	= 27.5 ***
C11	1	8.61	
C12	1	51.44	
C13	1	110.56	
C14	1	6.83	
C15	1	31.26	
C16	1	386.86	
C17	1	2.27	
C18	1	55.65	

APPENDIX 2b

REGRESSION ANALYSIS FOR MODEL 3

The regression equation is

GYC = 26.5 - 0.0404 ELEVATION - 2.99 C6 + 4.62 C7 + 5.48 C8 + 3.62 C9 + 7.08 C10
+ 6.60 C11 + 2.33 C12 + 2.85 C13 + 4.79 C14 + 1.51 C15 - 0.335 C16
+ 0.342 C17 - 7.15 C18 - 3.66 C19 + 8.23 C20 + 5.02 C21 - 0.56 C22
+ 4.01 C23 - 5.06 C24 - 4.02 C25 + 3.30 C26 - 4.63 C27 + 4.66 C28
- 0.26 C29 + 5.06 C30 - 5.64 C31 - 9.46 C32 + 6.35 C33 + 2.44 C34
- 8.81 C35 - 5.86 C36 - 0.59 C37 - 5.41 C38 + 3.48 C39 + 3.10 C40
+ 8.34 C41

Predictor	Coef	Stdev	t-ratio	
Constant	26.489	1.076	24.63	
ELEVATN	-0.040417	0.002565	-15.76	
C6	-2.9907	0.9024	-3.31	SOUTH KINTYRE
C7	4.6172	0.9438	4.89	CLATTERINGSHAWS
C8	5.4791	0.8213	6.67	STRATHYRE
C9	3.6170	0.8783	4.12	WAUCHOPE
C10	7.0845	0.9164	7.73	DRUMMOND HILL
C11	6.598	1.145	5.76	AE
C12	2.334	1.121	2.08	GLENSHIEL
C13	2.851	1.183	2.41	RATAGAN
C14	4.7860	0.8506	5.63	CRIANLARICH
C15	1.5149	0.9003	1.68	ARECLEOCH
C16	-0.3349	0.9349	-0.36	GLENTROOL
C17	0.3420	0.8774	0.39	BALLACHULISH
C18	-7.152	2.143	-3.34	SKIALL
C19	-3.663	1.535	-2.39	HELMSDALE
C20	8.2326	0.9422	8.74	OCHIL
C21	5.019	1.311	3.83	ANGUS
C22	-0.564	1.072	-0.53	ARRAN
C23	4.011	1.621	2.47	GLENTRESS
C24	-5.061	1.132	-4.47	BORGIE
C25	-4.019	1.115	-3.61	SUNART
C26	3.2968	0.9451	3.49	CLASHINDARROCH
C27	-4.631	2.107	-2.20	DEER (1)
C28	4.662	1.291	3.61	DRUMTOCHTY
C29	-0.262	1.511	-0.17	BALBLAIR
C30	5.063	2.042	2.48	CORROUR
C31	-5.635	2.114	-2.67	DEER (2)
C32	-9.459	1.457	-6.49	LEWIS
C33	6.354	1.679	3.78	QUEENS
C34	2.444	2.042	1.20	ROSARIE
C35	-8.811	2.142	-4.11	RUMSTER (1)
C36	-5.858	2.119	-2.76	RUMSTER (2)
C37	-0.593	2.083	-0.28	SHIN
C38	-5.405	2.131	-2.54	STRATHY
C39	3.482	1.564	2.23	TORRACHILTY
C40	3.104	2.065	1.50	WATERMEETINGS
C41	8.343	1.485	5.62	HAMSTERLEY

s = 1.946   R-sq = 80.7%   R-sq(adj) = 76.0%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	37	2377.759	64.264
Error	150	568.240	3.788
Total	187	2945.999	

APPENDIX 3

TESTING FOR DIFFERENCES IN SLOPE

Regression model 2 (with all 18 sites included separately) with intercepts allowed to vary but common slope.

The regression equation is

```
C3 = 28.7 - 0.0430 ELEVATION - 4.60 C6 + 3.61 C7 + 4.94 C8 + 2.37 C9 + 6.00 C10
          + 5.65 C11 + 1.31 C12 + 0.97 C13 + 3.40 C14 + 0.135 C15 - 1.53 C16
          + 7.22 C17 - 2.05 C18 - 5.71 C19 - 1.37 C20 + 1.94 C21 + 5.37 C22
```

Predictor	Coef	Stdev	t-ratio
Constant	28.740	1.137	25.28
ELEVATION	-0.042981	0.002244	-19.15
C6	-4.5977	0.9303	-4.94
C7	3.6128	0.9124	3.96
C8	4.9381	0.8946	5.52
C9	2.3652	0.8825	2.68
C10	6.0019	0.8974	6.69
C11	5.645	1.038	5.44
C12	1.310	1.023	1.28
C13	0.969	1.135	0.85
C14	3.4016	0.8765	3.88
C15	0.1352	0.9292	0.15
C16	-1.5276	0.9628	-1.59
C17	7.2241	0.9115	7.93
C18	-2.046	1.017	-2.01
C19	-5.713	1.067	-5.35
C20	-1.3691	0.8866	-1.54
C21	1.938	1.070	1.81
C22	5.370	1.035	5.19

s = 1.491 R-sq = 87.7% R-sq(adj) = 85.7%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	18	1804.18	100.23
Error	114	253.56	2.22
Total	132	2057.75	

Regression model 4 - intercepts and slopes free to vary.

The regression equation is

```
C3 = 39.2 - 12.4 C6 - 6.02 C7 - 11.9 C8 - 0.56 C9 - 9.83 C10 + 7.3 C11
          - 1.5 C12 - 11.9 C13 - 8.14 C14 - 10.2 C15 - 1.87 C16 + 6.09 C17
          - 12.2 C18 - 22.2 C19 - 12.3 C20 + 6.0 C21 + 39.9 C22 - 0.0537 C26
          - 0.0447 C27 - 0.0287 C28 - 0.0624 C29 - 0.0312 C30 - 0.0670 C31
```

- 0.0590 C32 - 0.0262 C33 - 0.0399 C34 - 0.0434 C35 - 0.0690 C36
- 0.0623 C37 - 0.0440 C38 - 0.0152 C39 - 0.0416 C40 - 0.0744 C41
- 0.133 C42 - 0.0704 C43

Predictor	Coef	Stdev	t-ratio
Constant	39.228	7.878	4.98
Intercepts			
C6	-12.389	8.038	-1.54
C7	-6.024	8.417	-0.72
C8	-11.949	8.231	-1.45
C9	-0.563	8.651	-0.07
C10	-9.832	8.332	-1.18
C11	7.34	13.13	0.56
C12	-1.49	11.38	-0.13
C13	-11.942	7.950	-1.50
C14	-8.136	8.070	-1.01
C15	-10.218	8.555	-1.19
C16	-1.868	9.536	-0.20
C17	6.094	8.224	0.74
C18	-12.228	8.190	-1.49
C19	-22.240	8.019	-2.77
C20	-12.346	8.146	-1.52
C21	5.98	12.36	0.48
C22	39.89	12.03	3.32
Slopes			
C26	-0.053721	0.006179	-8.69
C27	-0.044732	0.006051	-7.39
C28	-0.028706	0.005258	-5.46
C29	-0.062385	0.009127	-6.84
C30	-0.031247	0.005902	-5.29
C31	-0.06703	0.02073	-3.23
C32	-0.05904	0.01712	-3.45
C33	-0.026155	0.006468	-4.04
C34	-0.039875	0.005076	-7.86
C35	-0.04342	0.01081	-4.02
C36	-0.06900	0.01372	-5.03
C37	-0.062296	0.004812	-12.95
C38	-0.044000	0.007263	-6.06
C39	-0.015152	0.006472	-2.34
C40	-0.041560	0.005934	-7.00
C41	-0.07440	0.02054	-3.62
C42	-0.13300	0.01816	-7.33
C43	-0.07040	0.02054	-3.43

s = 1.148   R-sq = 93.8%   R-sq(adj) = 91.5%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	35	1929.840	55.138
Error	97	127.906	1.319
Total	132	2057.746	

TEST OF SIGNIFICANCE FOR EFFECT OF FREELY VARYING SLOPE:

{(253.6 - 127.91)/(114-97)}/2.220 = 3.33 **

APPENDIX 4

ACCUMULATED TEMPERATURE DATA

EQUATIONS FOR TEMPERATURE AGAINST ELEVATION.

STATION	GRID REF	EQUATION: ACC. TEMP v ELEVATION
STORNOWAY	NX450330	$Y = 1280 - 1.68\,E + 0.0006\,E2$
WICK	ND360520	$Y = 1182 - 1.62\,E + 0.0006\,E^2$
ACHNASHELLACH	NH030490	$Y = 1421 - 1.64\,E + 0.0005\,E^2$
FORTROSE	NH720560	$Y = 1483 - 1.64\,E + 0.0005\,E^2$
FORT AUGUSTUS	NH380090	$Y = 1408 - 1.59\,E + 0.0005\,E^2$
INVERNESS	NH660410	$Y = 1465 - 1.66\,E + 0.0005\,E^2$
GORDAN CASTLE	NJ350590	$Y = 1474 - 1.65\,E + 0.0005\,E^2$
BANFF	NJ680640	$Y = 1456 - 1.67\,E + 0.0005\,E^2$
ABERDEEN	NJ940080	$Y = 1379 - 1.63\,E + 0.0005\,E^2$
BRAEMAR	NO150910	$Y = 1514 - 1.66\,E + 0.0005\,E^2$
CRAIBSTONE	NJ870100	$Y = 1364 - 1.62\,E + 0.0005\,E^2$
LOGIE COLDSTONE	NJ440040	$Y = 1449 - 1.59\,E + 0.0005\,E^2$
ARBROATH	NO640430	$Y = 1418 - 1.63\,E + 0.0005\,E^2$
DUNDEE	NO430310	$Y = 1512 - 1.61\,E + 0.0004\,E^2$
KETTINS	NO230390	$Y = 1438 - 1.58\,E + 0.0005\,E^2$
PERTH	NO020340	$Y = 1555 - 1.61\,E + 0.0004\,E^2$
CUPAR	NO370140	$Y = 1522 - 1.62\,E + 0.0004\,E^2$
KIRKCALDY	NO270930	$Y = 1574 - 1.65\,E + 0.0004\,E^2$
LEUCHARS	NO460200	$Y = 1454 - 1.63\,E + 0.0005\,E^2$
ST. ANDREWS	NT500160	$Y = 1442 - 1.61\,E + 0.0005\,E^2$
BOGHALL	NT240650	$Y = 1621 - 1.72\,E + 0.0005\,E^2$
EDINBURGH	NT250700	$Y = 1674 - 1.73\,E + 0.0004\,E^2$
NORTH BERWICK	NT550480	$Y = 1538 - 1.67\,E + 0.0005\,E^2$
MARCHMONT	NT740480	$Y = 1560 - 1.66\,E + 0.0005\,E^2$
WEST LINTON	NT150510	$Y = 1490 - 1.60\,E + 0.0004\,E^2$
KELSO	NT740350	$Y = 1507 - 1.62\,E + 0.0005\,E^2$
WOLFLEE	NT580090	$Y = 1472 - 1.62\,E + 0.0005\,E^2$
ARDTONISH	NM700470	$Y = 1458 - 1.68\,E + 0.0005\,E^2$
GLENBRANTER	NS110970	$Y = 1450 - 1.67\,E + 0.0005\,E^2$
ROTHESAY	NS100640	$Y = 1558 - 1.76\,E + 0.0005\,E^2$
CARDROSS	NS350770	$Y = 1489 - 1.66\,E + 0.0005\,E^2$
HELENSBURGH	NS300830	$Y = 1610 - 1.72\,E + 0.0005\,E^2$
STIRLING	NS790930	$Y = 1656 - 1.67\,E + 0.0004\,E^2$
GREENOCK	NS270750	$Y = 1687 - 1.74\,E + 0.0004\,E^2$
PAISLEY	NS470640	$Y = 1720 - 1.71\,E + 0.0004\,E^2$
RENFREW	NS500660	$Y = 1520 - 1.63\,E + 0.0004\,E^2$
DUNGAVEL	NS650370	$Y = 1490 - 1.64\,E + 0.0005\,E^2$
COLMONELL	NE20850	$Y = 1612 - 1.75\,E + 0.0005\,E^2$
KILMARNOCK	NS430380	$Y = 1638 - 1.69\,E + 0.0004\,E^2$
TURNBERRY	NS200050	$Y = 1632 - 1.78\,E + 0.0005\,E^2$
DUMFRIES	NX980730	$Y = 1578 - 1.68\,E + 0.0005\,E^2$
ESKDALEMIUR	NT230020	$Y = 1456 - 1.65\,E + 0.0005\,E^2$
RUTHWELL	NY070690	$Y = 1545 - 1.64\,E + 0.0004\,E^2$
KINGUSSIE	NH760000	$Y = 1482 - 1.58\,E + 0.0004\,E^2$
BALRUDDERY	NO300320	$Y = 1439 - 1.62\,E + 0.0005\,E^2$
FORT WILLIAM	NN100730	$Y = 1512 - 1.67\,E + 0.0005\,E^2$
STRATHPEFFER	NH480580	$Y = 1376 - 1.59\,E + 0.0005\,E^2$
CRIEFF	NN860220	$Y = 1638 - 1.66\,E + 0.0004\,E^2$
CALLY	NX590540	$Y = 1547 - 1.73\,E + 0.0005\,E^2$
DUNROBIN	NC850000	$Y = 1281 - 1.64\,E + 0.0006\,E^2$
GLENCARRON	NH060510	$Y = 1433 - 1.65\,E + 0.0005\,E^2$

STATION	GRID REF	EQUATION: SUMMER TEMP v ELEVATION
DEERNESS	HY560050	$Y = 1191 - 1.59\ E + 0.0006\ E2$
NEW PITSLIGO	NJ880560	$Y = 1432 - 1.63\ E + 0.0005\ E^2$
PITLOCHRY	NN940580	$Y = 1630 - 1.63\ E + 0.0004\ E^2$
EALLABUS	NR330630	$Y = 1477 - 1.63\ E + 0.0005\ E^2$
LAIRG	NC600050	$Y = 1260 - 1.55\ E + 0.0005\ E^2$
DUNVEGAN	NG250470	$Y = 1375 - 1.71\ E + 0.0005\ E^2$
SCOURIE	NC150440	$Y = 1239 - 1.54\ E + 0.0005\ E^2$
KIRKCOWAN	NX320610	$Y = 1563 - 1.73\ E + 0.0005\ E^2$
TONGUE	NC590590	$Y = 1250 - 1.55\ E + 0.0005\ E^2$
KESWICK	NY260238	1774
NEWTON RIGG	NY493310	1664
APPELBY	NY685197	1635
BELLINGHAM	NY808911	1574
BERWICK ON TWEED	NU002258	1437
MORPETH	NZ210912	1515
TYNEMOUTH	NZ373677	1655
CHOPWELL WOOD	NZ136580	1654
DURHAM	NZ264416	1685
HOUGHALL	NZ283412	1626
USHAW	NZ219436	1766

APPENDIX 5

REGRESSION ANALYSIS FOR MODEL 8 - TATTER MODEL

Coordinates give locations of sites in metres relative

national grid origin (easting, northing).

SITE	SITE-COEFF	STAND. ERROR	T-RATIO	COORDINATES	
SITE 1	12.145	0.702	17.29	121400	656300
SITE 2	11.81	1.58	7.49	203500	932600
SITE 3	10.668	0.861	12.39	324400	1001700
SITE 4	10.668	0.719	14.84	146600	722200
SITE 5	11.661	0.865	13.48	79700	870300
SITE 6	13.69	1.05	13.08	183600	823300
SITE 7	11.61	1.02	11.42	171000	819200
SITE 8	10.53	1.11	9.44	170200	613900
SITE 9	14.331	0.892	16.06	155400	767700
SITE 10	6.20	1.58	3.93	238000	623400
SITE 11	7.36	1.62	4.55	227300	615400
SITE 12	9.45	1.15	8.25	281700	959500
SITE 13	8.890	0.932	9.54	266600	953600
SITE 14	10.970	0.698	15.71	174400	644300
SITE 15	7.69	1.58	4.85	200200	893700
SITE 16	11.889	0.895	13.28	189300	725700
SITE 17	8.637	0.856	10.09	157800	753800
SITE 18	8.93	1.19	7.51	398300	858300
SITE 19	7.81	1.24	6.30	289400	939600
SITE 20	11.995	0.813	14.76	151200	743000
SITE 21	8.757	0.787	11.13	292100	949400
SITE 22	9.47	1.58	6.00	219900	936400
SITE 23	7.998	0.986	8.11	316400	955700
SITE 24	8.60	1.02	8.41	310100	943400
SITE 25	9.762	0.764	12.77	232600	911200
SITE 26	8.60	1.01	8.54	235800	899200
SITE 27	7.134	0.768	9.29	169300	632700
SITE 28	10.560	0.960	11.00	184200	675400
SITE 29	7.577	0.762	9.95	224700	578000
SITE 30	7.367	0.828	8.89	198000	705400
SITE 31	6.300	0.845	7.45	166400	746800
SITE 32	8.31	1.07	7.79	204400	712300
SITE 33	2.14	1.15	1.86	184100	770200
SITE 34	8.347	0.983	8.50	197400	700900
SITE 35	7.93	1.02	7.80	257200	940500
SITE 36	6.904	0.990	6.97	316600	950000
SITE 37	10.06	1.60	6.27	329000	942700
SITE 38	7.436	0.884	8.41	246200	926800
SITE 39	7.090	0.689	10.29	289700	565600
SITE 40	6.835	0.960	7.12	229900	862500
SITE 41	5.27	1.06	4.99	260800	627100
SITE 42	5.14	1.26	4.08	247500	895600
SITE 43	9.11	1.08	8.46	220300	604000
SITE 44	5.560	0.832	6.68	378200	791900
SITE 45	7.094	0.870	8.15	214600	674600
SITE 46	3.20	1.63	1.96	327600	596400
SITE 47	6.20	1.33	4.68	250200	583800
SITE 48	4.978	0.914	5.44	268500	601900
SITE 49	8.039	0.938	8.57	245300	679300

SITE	SITE-COEFF	STAND. ERROR	T-RATIO	COORDINATES	
SITE 50	7.70	1.12	6.85	214600	711000
SITE 51	5.79	1.19	4.88	313000	624700
SITE 52	8.61	1.18	7.30	209500	757100
SITE 53	7.45	1.11	6.69	207200	693200
SITE 54	6.22	1.10	5.64	270500	606000
SITE 55	5.11	1.18	4.34	320700	648500
SITE 56	6.375	0.884	7.21	237500	592700
SITE 57	4.913	0.911	5.40	298500	617500
SITE 58	6.074	0.878	6.91	288800	927300
SITE 59	8.208	0.849	9.67	334100	605600
SITE 60	6.030	0.837	7.20	364900	598300
SITE 61	8.388	0.944	8.89	249900	568700
SITE 62	5.04	1.02	4.97	320600	606800
SITE 63	4.43	1.77	2.50	207400	743600
SITE 64	4.86	1.02	4.76	306300	623400
SITE 65	4.39	1.61	2.73	259500	913800
SITE 66	4.95	1.22	4.06	367000	572400
SITE 68	3.80	1.60	2.38	379500	578700
SITE 69	6.122	0.863	7.10	361800	599500
SITE 70	6.001	0.730	8.23	266800	634700
SITE 71	5.266	0.981	5.37	255000	702700
SITE 72	3.08	1.02	3.00	230700	824300
SITE 73	3.24	1.18	2.74	328600	777300
SITE 74	3.76	1.00	3.74	267200	875500
SITE 75	6.20	1.26	4.90	235800	729300
SITE 76	3.341	0.933	3.58	342900	856800
SITE 77	4.66	1.14	4.10	354400	823000
SITE 78	5.295	0.968	5.47	304800	706100
SITE 79	4.73	1.09	4.34	328300	763900
SITE 80	2.712	0.970	2.80	272500	681800
SITE 81	4.304	0.956	4.50	355200	832700
SITE 82	3.91	1.22	3.21	219100	791600
SITE 83	2.238	0.995	2.25	314300	818100
SITE 84	4.73	1.06	4.47	338600	618400
SITE 85	1.031	0.856	1.21	263400	833500
SITE 86	5.17	1.66	3.12	245600	812000
SITE 87	6.88	1.14	6.01	237100	728800
SITE 88	8.88	1.07	8.32	219800	798300
SITE 89	8.36	1.87	4.47	231200	796400
SITE 90	4.11	1.05	3.91	321200	816000
SITE 91	6.45	1.07	6.01	231800	734900
SITE 92	7.007	0.930	7.53	205800	764100
SITE 93	5.20	1.03	5.04	330500	641600
SITE 94	3.700	0.955	3.88	255200	836700
SITE 95	3.72	1.19	3.12	380400	543800
SITE 96	4.99	1.10	4.53	396600	594300
SITE 97	3.36	1.07	3.13	341500	827600
SITE 98	3.726	0.816	4.57	226500	815200
SITE 99	3.895	0.943	4.13	383700	609700

SITE	SITE-COEFF	STAND. ERROR	T-RATIO	COORDINATES	
SITE 100	3.378	0.819	4.12	369500	782000
SITE 101	3.55	1.07	3.32	245800	852700
SITE 102	5.92	1.65	3.58	230600	751200
SITE 103	2.14	1.63	1.31	319400	749300
SITE 104	4.27	1.00	4.26	238700	778700
SITE 105	3.161	0.740	4.27	278400	709400
SITE 106	4.44	1.22	3.63	244600	867600
SITE 107	3.50	1.20	2.91	371200	612100
SITE 108	7.86	1.52	5.17	333800	966200
SITE 109	3.309	0.887	3.73	334500	843500

FACTOR	COEFF.	Standard error	t-ratio	
ELEVN.	0.01932	0.00144	13.37	ELEVATION
ASPECT 1	-1.631	0.448	-3.65	N
ASPECT 2	-1.895	0.424	-4.47	NE
ASPECT 3	-2.328	0.485	-4.80	E
ASPECT 4	-1.841	0.410	-4.49	SE
ASPECT 5	-1.164	0.423	-2.75	S
ASPECT 6	-0.899	0.403	-2.23	SW
ASPECT 7	-1.376	0.426	-3.23	W
ASPECT 8	-1.249	0.407	-3.07	NW
ASPECT 9	-1.316	0.613	-2.15	NIL
ASPECT 10	0	*	*	ALL (ref. category)
TOPEX	0.06249	0.00614	-10.17	TOPEX

*** ANALYSIS OF VARIANCE ***

	DF	SS	MS
REGRESSN	120	62026	516.884
RESIDUAL	444	1021	2.300
TOTAL	564	63047	111.786

PERCENTAGE VARIANCE ACCOUNTED FOR 76.7

APPENDIX 6

BEST REGRESSION MODELS

Note that intercept values and the values for the coefficients for the dummy variables are not identical to those in table 14 because the latter have been adjusted to give values for the dummy variables which are relative to their average value, not to the reference category.

MODEL 52

The regression equation is

GYC = 19.9 - 1.02 tatter + 0.00833 acc.tem - 0.127 age - 0.107 slope + 1.56 BE
- 0.79 POO - 0.48 IP - 0.69 PG + 0.05 SWG - 1.30 FP - 1.61 BB
- 2.62 UP

Predictor	Coef	Stdev	t-ratio
Constant	19.913	2.402	8.29
tatter	-1.01536	0.08613	-11.79
acc.tem	0.008333	0.001388	6.00
age	-0.12701	0.01544	-8.23
slope	-0.10709	0.02260	-4.74
BE	1.563	1.124	1.39
POO	-0.789	1.194	-0.66
IP	-0.478	1.084	-0.44
PG	-0.691	1.042	-0.66
SWG	0.046	1.053	0.04
FP	-1.300	1.102	-1.18
BB	-1.607	1.752	-0.92
UP	-2.616	1.212	-2.16

s = 1.941   R-sq = 77.6%   R-sq(adj) = 76.1%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	12	2286.91	190.58
Error	175	659.09	3.77
Total	187	2946.00	

SOURCE	DF	SEQ SS
cosine	1	1016.63
acc.tem	1	716.88
age	1	386.21
slope	1	64.68
BE	1	44.88
POO	1	0.12
IP	1	0.66
PG	1	1.41
SWG	1	33.23
FP	1	4.49
BB	1	0.17
UP	1	17.55

MODEL 53

The regression equation is

```
GYC = 21.3 - 0.0320 elevatn - 1.02 tatt.sl + 0.00807 a.te.sl. + 0.0332 topex
           - 0.109 age + 0.97 valley - 1.73 hilltop + 1.17 sine + 0.328 cosine
           + 1.69 BE - 0.07 POD + 0.06 IP + 0.01 PG + 0.72 SWG - 0.79 FP
           - 2.50 BB - 2.24 UP  + o cc βk.
```

Predictor	Coef	Stdev	t-ratio
Constant	21.310	3.122	6.83
elevatn	-0.032040	0.001661	-19.29
tatt.sl	-1.0160	0.1138	-8.93
a.te.sl.	0.008069	0.001859	4.34
topex	0.033234	0.007719	4.31
age	-0.10935	0.01856	-5.89
valley	0.971	1.440	0.67
hilltop	-1.7308	0.9655	-1.79
sine	1.1664	0.2083	5.60
cos	0.3280	0.2457	1.33
BE	1.694	1.112	1.52
POD	-0.067	1.196	-0.06
IP	0.059	1.077	0.05
PG	0.008	1.027	0.01
SWG	0.724	1.030	0.70
FP	-0.790	1.078	-0.73
BB	-2.498	1.758	-1.42
UP	-2.237	1.208	-1.85

s = 1.895   R-sq = 79.3%   R-sq(adj) = 77.2%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	17	2335.23	137.37
Error	170	610.77	3.59
Total	187	2946.00	

SOURCE	DF	SEQ SS
elevatn	1	1063.53
tatt.sl	1	668.25
a.te.sl.	1	237.36
topex	1	31.84
age	1	95.66
valley	1	4.03
hilltop	1	17.16
sine	1	122.07
cosine	1	5.15
BE	1	24.38
POD	1	0.30
IP	1	0.37
PG	1	3.93
SWG	1	39.05

FP	1	8.75
BB	1	1.07
UP	1	12.32

MODEL 56

The regression equation is
GYC = 21.4 - 1.11 TATTER + 0.00966 ACC.TEM - 0.153 AGE - 0.108 C9 + 0.47 BE
- 2.77 POO - 2.87 IP - 1.70 PG - 1.05 SWG - 2.45 FP - 2.98 BB
- 3.88 UP

Predictor	Coef	Stdev	t-ratio
Constant	21.371	3.049	7.01
TATTER	-1.11051	0.09436	-11.77
ACC.TEM	0.009665	0.001444	6.69
AGE	-0.15327	0.03071	-4.99
C9	-0.10834	0.02660	-4.07
BE	0.470	1.998	0.24
POO	-2.767	1.928	-1.43
IP	-2.875	1.855	-1.55
PG	-1.703	1.799	-0.95
SWG	-1.052	1.843	-0.57
FP	-2.455	1.798	-1.37
BB	-2.975	2.202	-1.35
UP	-3.879	1.874	-2.07

s = 1.748   R-sq = 83.8%   R-sq(adj) = 82.3%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	12	2039.16	169.93
Error	129	394.07	3.05
Total	141	2433.23	

SOURCE	DF	SEQ SS
TATTER	1	1457.06
ACC.TEM	1	435.30
AGE	1	30.81
C9	1	25.65
BE	1	21.16
POO	1	4.16
IP	1	8.45
PG	1	5.74
SWG	1	29.58
FP	1	7.66
BB	1	0.50
UP	1	13.08

MODEL 55

The regression equation is
GYC = 21.4 - 0.0369 ELEVATN - 1.21 TATT.SL. + 0.0114 A.TE.SL + 0.0399 TOPEX

- 0.124 AGE - 0.03 VALLEY - 1.79 HILL + 0.822 SINE + 0.352 COSINE
- 0.64 BE - 2.83 POD - 2.95 IP - 1.87 PG - 1.40 SWG - 2.66 FP
- 4.21 BB - 4.01 UP

Predictor	Coef	Stdev	t-ratio
Constant	21.382	3.942	5.42
ELEVATN	-0.036919	0.002138	-17.27
TATT.SL.	-1.2121	0.1370	-8.85
A.TE.SL	0.011443	0.002147	5.33
TOPEX	0.039876	0.009797	4.07
AGE	-0.12409	0.03113	-3.99
VALLEY	-0.031	1.392	-0.02
HILL	-1.790	1.004	-1.78
SINE	0.8217	0.2498	3.29
COSINE	0.3515	0.2812	1.25
BE	-0.642	2.136	-0.30
POD	-2.826	2.039	-1.39
IP	-2.953	1.947	-1.52
PG	-1.873	1.878	-1.00
SWG	-1.402	1.952	-0.72
FP	-2.659	1.885	-1.41
BB	-4.212	2.300	-1.83
UP	-4.008	1.988	-2.02

s = 1.779 R-sq = 83.9% R-sq(adj) = 81.7%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	17	2040.95	120.06
Error	124	392.27	3.16
Total	141	2433.23	

SOURCE	DF	SEQ SS
ELEVATN	1	998.37
TATT.SL.	1	459.86
A.TE.SL	1	308.27
TOPEX	1	123.12
AGE	1	21.24
VALLEY	1	0.20
HILL	1	27.21
SINE	1	44.03
COSINE	1	3.60
BE	1	4.90
POD	1	4.12
IP	1	3.00
PG	1	4.77
SWG	1	18.25
FP	1	6.58
BB	1	0.57
UP	1	12.85

APPENDIX 7

REGRESSION EQUATIONS FOR CALCULATION OF CONFIDENCE LIMITS.

MODEL 52 plus dummy variables for sites

The regression equation is

C3 = 23.7 - 1.31 TATTER + 0.00673 ACC. TEMP - 0.0742 SLOPE - 0.156 AGE + 0.23 BE
- 1.91 POO - 1.91 IP - 2.34 PG - 1.10 SWG - 3.42 FP - 1.51 BB
- 5.11 FP + 2.90 C30 + 2.28 C31 + 2.34 C32 + 2.95 C33 - 0.484 C34
+ 3.93 C35 + 4.70 C36 + 2.67 C37 + 3.38 C38 + 3.90 C39 + 2.38 C40
+ 0.74 C41 + 3.56 C42 + 2.70 C43 + 1.49 C44 - 1.96 C45 + 2.84 C46
+ 2.62 C47 + 3.46 C48 - 2.89 C49 + 2.48 C50 + 1.94 C51 + 1.80 C52
+ 6.90 C54 + 2.64 C55 + 2.51 C56 - 0.81 C57 + 0.20 C58 + 2.30 C59
+ 4.15 C60 + 3.71 C61 + 3.17 C62 + 3.12 C63 + 2.21 C64 + 3.91 C65

Predictor	Coef	Stdev	t-ratio
Constant	23.719	5.394	4.40
TATTER	-1.3062	0.1768	-7.39
ACC.TEMP	0.006731	0.003752	1.79
SLOPE	-0.07420	0.02943	-2.52
AGE	-0.15595	0.02623	-5.94
BE	0.2349	0.9933	0.24
POO	-1.912	1.057	-1.81
IP	-1.9117	0.9782	-1.95
PG	-2.3424	0.8925	-2.62
SWG	-1.1021	0.9023	-1.22
FP	-3.4189	0.9612	-3.56
BB	-1.513	1.640	-0.92
UP	-5.114	1.255	-4.08
SITES			
C30	2.904	1.170	2.48
C31	2.2786	0.7376	3.09
C32	2.3416	0.8071	2.90
C33	2.9451	0.7975	3.69
C34	-0.4841	0.8686	-0.56
C35	3.9260	0.9322	4.21
C36	4.704	1.254	3.75
C37	2.671	1.010	2.64
C38	3.3771	0.7536	4.48
C39	3.900	1.224	3.18
C40	2.378	1.145	2.08
C41	0.740	1.117	0.66
C42	3.564	1.685	2.12
C43	2.699	1.292	2.09
C44	1.4913	0.7717	1.93
C45	-1.961	1.326	-1.48
C46	2.840	1.302	2.18
C47	2.618	1.297	2.02
C48	3.4624	0.9026	3.84
C49	-2.889	1.150	-2.51
C50	2.4788	0.9082	2.73

C51	1.941	1.866	1.04
C52	1.800	1.274	1.41
C54	6.904	1.922	3.59
C55	2.644	1.941	1.36
C56	2.514	1.761	1.43
C57	-0.814	1.635	-0.50
C58	0.201	1.742	0.12
C59	2.296	1.963	1.17
C60	4.146	1.967	2.11
C61	3.709	1.956	1.90
C62	3.172	1.706	1.86
C63	3.117	1.577	1.98
C64	2.207	1.681	1.31
C65	3.915	1.217	3.22

s = 1.548 R-sq = 88.6% R-sq(adj) = 84.8%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	47	2610.585	55.544
Error	140	335.413	2.396
Total	187	2945.999	

SOURCE	DF	SEQ SS
TATTER	1	1016.632
ACC.TEMP	1	716.882
SLOPE	1	208.466
AGE	1	242.420
BE	1	44.879
POD	1	0.121
IP	1	0.657
PG	1	1.410
SWG	1	33.230
FP	1	4.490
88	1	0.174
UP	1	17.547

SITES

C30	1	3.711
C31	1	0.431
C32	1	15.449
C33	1	1.354
C34	1	29.866
C35	1	11.346
C36	1	70.928
C37	1	9.948
C38	1	26.361
C39	1	6.328
C40	1	0.292
C41	1	14.013
C42	1	5.338
C43	1	0.143
C44	1	2.389
C45	1	22.838
C46	1	0.860

C47	1	2.398
C48	1	13.928
C49	1	18.751
C50	1	5.704
C51	1	0.073
C52	1	0.872
C53	1	0.137
C54	1	0.078
C55	1	0.395
C56	1	0.135
C57	1	5.352
C58	1	1.658
C59	1	0.254
C60	1	1.666
C61	1	2.145
C62	1	2.473
C63	1	4.726
C64	1	1.449
C65	1	24.792

Total SS for sites = 232.95

F-ratio for sites = (232.95/36)/3.77)

where 3.77 = RMS for model 52

MODEL 55 plus dummy variables for site

The regression equation is
C3 = - 13.0 - 0.0368 ELEV - 0.285 TATT.S.L. + 0.0282 A.TE.S.L. + 0.0677 TOP - 0.154 AGE
+ 1.08 SIN - 0.449 COS + 0.58 BE - 1.95 POO - 1.76 IP - 1.87 PG
- 0.604 SWG - 2.77 FP + 4.50 BB - 4.25 UP + 1.31 C30 - 2.22 C31
+ 0.55 C32 + 0.79 C33 + 2.55 C34 + 4.68 C35 + 0.25 C36 + 4.60 C37
+ 4.58 C38 + 1.71 C39 + 3.26 C40 - 0.09 C41 - 0.09 C42 + 0.02 C43
+ 7.4 C44 + 5.9 C45 + 2.27 C46 + 2.54 C47 - 0.46 C48 + 4.13 C49
+ 6.6 C50 - 3.33 C51 + 6.11 C52 + 1.55 C53 + 7.37 C54 + 8.59 C56
+ 1.85 C57 - 0.20 C58 + 3.86 C59 + 5.45 C60 + 7.4 C61 + 9.4 C62
+ 8.55 C63 + 5.6 C64 + 7.60 C65

Predictor	Coef	Stdev	t-ratio
Constant	-13.03	69.49	-0.19
ELEVATION	-0.036779	0.002396	-15.35
TATTER S.L.	-0.2848	0.8257	-0.34
A.TEMP. S.L.	0.02817	0.04682	0.60
TOPEX	0.06767	0.01334	5.07
AGE	-0.15426	0.02713	-5.69
SINE	1.0770	0.2729	3.95
COSINE	-0.4491	0.4680	-0.96
BE	0.581	1.011	0.58
POO	-1.952	1.075	-1.82
IP	-1.7627	0.9762	-1.81
PG	-1.8694	0.8940	-2.09
SWG	-0.6037	0.9086	-0.66
UP	-2.7716	0.9580	-2.89

BB	4.503	9.194	0.49
FP	-4.250	1.304	-3.26

SITES

C30	1.307	1.366	0.96
C31	-2.216	1.282	-1.73
C32	0.553	2.054	0.27
C33	0.785	4.791	0.16
C34	2.549	5.273	0.48
C35	4.679	2.567	1.82
C36	0.254	6.847	0.04
C37	4.599	3.664	1.26
C38	4.579	2.044	2.24
C39	1.715	2.216	0.77
C40	3.256	3.623	0.90
C41	-0.093	6.118	-0.02
C42	-0.094	4.814	-0.02
C43	0.024	1.302	0.02
C44	7.42	13.83	0.54
C45	5.86	11.54	0.51
C46	2.274	7.333	0.31
C47	2.539	4.112	0.62
C48	-0.459	3.810	-0.12
C49	4.125	2.579	1.60
C50	6.58	11.51	0.57
C51	-3.325	2.012	-1.65
C52	6.113	3.065	1.99
C53	1.552	4.488	0.35
C54	7.371	4.906	1.50
C56	8.591	2.897	2.97
C57	1.853	4.114	0.45
C58	-0.202	7.961	-0.03
C59	3.858	3.609	1.07
C60	5.448	3.960	1.38
C61	7.42	12.75	0.58
C62	9.36	12.75	0.73
C63	8.555	8.503	1.01
C64	5.64	13.56	0.42
C65	7.596	5.519	1.38

s = 1.510   R-sq = 89.6%   R-sq(adj) = 85.5%

Analysis of Variance

SOURCE	DF	SS	MS
Regression	52	2638.354	50.738
Error	135	307.645	2.279
Total	187	2945.999	

SOURCE	DF	SEQ SS
ELEVATION	1	1063.531
TATTER S.L.	1	668.254
A.TEMP. S.L.	1	237.361
TOPEX	1	31.844
AGE	1	95.663
SINE	1	121.911

COSINE	1	5.574
BE	1	24.674
POO	1	0.016
IP	1	0.066
PG	1	4.192
SWG	1	41.623
FP	1	12.428
BB	1	0.211
UP	1	14.549

SITES

C30	1	1.787
C31	1	11.546
C32	1	0.021
C33	1	4.599
C34	1	15.381
C35	1	15.155
C36	1	52.971
C37	1	2.321
C38	1	57.962
C39	1	0.159
C40	1	29.595
C41	1	1.097
C42	1	0.004
C43	1	26.655
C44	1	2.142
C45	1	1.050
C46	1	5.216
C47	1	3.625
C48	1	2.051
C49	1	1.642
C50	1	9.874
C51	1	40.326
C52	1	0.801
C53	1	0.137
C54	1	0.078
C56	1	8.186
C57	1	0.718
C58	1	0.109
C59	1	2.660
C60	1	2.092
C61	1	0.186
C62	1	4.688
C63	1	0.001
C64	1	0.828
C65	1	6.544

APPENDIX 8a

VALIDATION SURVEY DATA.

DISTRICT	FOREST	GRID REF	GYC	ELE	ASP	TOP	SL	AG	ST	TATT S.L.	A.TE S.L.
Cowal	Glendarual	NS067918	10.4	340	210	31	10	22	9	8.0	1500
Cowal	Glendarual	NS165830	16.3	275	205	53	18	22	6	7.4	1540
Cowal	Glendarual	NS067917	13.4	310	205	30	11	22	6	8.0	1500
Dornoch	Dornoch	NH762936	16.6	160	000	7	0	16	6	4.0	1320
Dornoch	Shin	NC535212	20.6	180	225	28	7	17	6	5.6	1250
Dornoch	Rumster	ND217402	16.9	160	247	20	3	19	7	8.3	1220
Dornoch	Rumster	NC556006	17.4	250	45	20	6	17	11	5.0	1300
Dornoch	Naver	NC673538	24.0	140	90	19	6	16	9	9.0	1240
Dornoch	Naver	NC669538	18.0	175	90	16	5	16	9	9.0	1240
Ardgartan	Glen Orchy	NN459271	17.3	274	320	88	17	22	7	6.2	1540
Ardgartan	Glen Orchy	NN463268	13.6	400	300	64	21	22	6	6.2	1540
Kintyre	Achaglachach	NR741662	13.9	215	330	23	13	21	6	10.0	1510
Kintyre	Achaglachach	NR749663	17.6	200	325	26	10	21	6	10.0	1510
Kintyre	S. Kintyre	NR734279	13.3	270	240	22	13	22	6	9.0	1520
Kintyre	S. Kintyre	NR732277	15.0	240	250	20	7	22	6	9.0	1520
Kintyre	S. Kintyre	NR729276	18.0	215	275	21	6	22	7	9.0	1520
Lockerbie	Moffat	NS974084	19.0	350	120	35	8	21	7	4.8	1520
Lockerbie	Moffat	NS972083	13.1	390	120	34	12	28	6	4.8	1520
Lockerbie	Moffat	NS968083	13.3	430	120	31	15	28	6	4.8	1520
Lockerbie	Moffat	NS966083	12.0	460	120	26	15	28	6	4.8	1520
Strontian	Sunart	NM828609	23.0	18	180	83	9	34	1	6.0	1460
Strontian	Sunart	NM828614	20.8	152	180	62	18	34	3	6.0	1460
Strontian	Sunart	NM829615	9.3	210	180	40	8	34	11	6.0	1460
Strontian	Sunart	NM833615	14.0	219	180	47	10	34	3	7.0	1450
Mull	Mull	NM529245	18.2	122	270	55	9	19	3	10.0	1450
Mull	Mull	NM532246	15.0	177	270	46	3	19	3	10.0	1450
Mull	Mull	NM535249	15.1	253	270	35	9	19	9	10.0	1450
Lothian	Cloich	NT198458	12.9	405	0	18	1	21	6	4.5	1560
Lothian		NT067594	17.0	275	0	11	2	19	6	5.0	1600
Lockerbie	Moffat	NT049157	15.6	380	10	25	8	22	6	5.0	1520
Lockerbie	Moffat	NT047156	15.3	395	330	23	8	22	4	5.0	1520
Lockerbie	Moffat	NT045153	18.0	410	0	30	10	22	7	5.0	1520
Lockerbie	Moffat	NT045148	13.8	435	20	16	9	22	9	5.0	1520
Lockerbie	Moffat	NT053154	16.0	370	280	28	13	23	7	5.0	1520
Lockerbie	Moffat	NT056157	15.8	415	270	20	11	23	6	5.0	1520
Lockerbie	Moffat	NT057157	12.0	445	27	11	8	23	6	5.0	1520

ASP = ASPECT
TOP = TOPEX
SL = SLOPE
AG = CROP AGE
ST = SOIL TYPE
TATT S.L. = ESTIMATED TATTER RATE AT SEA-LEVEL
A.TE S.L. = ESTIMATED ACCUMULATED TEMPERATURE AT SEA-LEVEL

APPENDIX 8b

VALIDATION SURVEY RESULTS

GYC ACT.	ELE	BUS	DIFF	MODEL 53	DIFF	MODEL 55	DIFF	MODEL 52	DIFF	MODEL 56	DIFF
				PREDICTED GYC							
10.4	340	12	1.6	11.41	1.01	11.46	1.06	11.27	0.87	11.33	0.93
16.3	275	14	-2.3	16.00	-0.29	16.70	0.40	15.42	-0.87	16.08	-0.21
13.4	310	12	-1.4	13.18	-0.21	13.31	-0.08	12.67	-0.72	12.98	-0.41
16.6	160	8	-8.6	19.56	2.96	20.33	3.73	19.26	2.66	20.16	3.56
20.6	180	9	11.6	17.98	-2.61	18.54	-2.05	17.90	-2.69	18.66	-1.93
16.9	160	10	-6.9	15.70	-1.19	15.50	-1.39	15.84	-1.05	16.20	-0.69
17.4	250	5	12.4	16.36	-1.03	16.45	-0.94	15.48	-1.91	15.91	-1.48
18.0	175	9	-9.0	15.76	-2.23	15.06	-2.93	14.68	-3.31	15.06	-2.93
17.3	274	18	0.7	19.42	2.12	20.46	3.16	19.82	2.52	20.70	3.40
13.6	400	14	0.4	13.53	-0.06	14.11	0.51	13.08	-0.51	13.46	-0.13
13.9	215	10	-3.9	14.63	0.73	14.91	1.01	13.32	-0.57	13.80	-0.09
17.6	200	11	-6.6	15.11	-2.48	15.51	-2.08	14.25	-3.34	14.80	-2.79
13.3	270	10	-3.3	12.95	-0.34	13.26	-0.03	12.10	-1.19	12.41	-0.88
15.0	240	10	-5.0	13.81	-1.18	14.28	-0.71	13.52	-1.47	13.94	-1.05
18.0	215	14	-4.0	15.43	-2.56	15.82	-2.17	15.24	-2.75	15.66	-2.33
19.0	350	15	-4.0	17.95	-1.04	17.93	-1.06	17.28	-1.71	17.80	-1.19
13.1	390	13	-0.1	15.17	2.07	15.07	1.97	13.94	0.84	14.22	1.12
13.3	430	13	-0.3	13.79	0.49	13.48	0.18	12.23	-1.06	12.35	-0.94
12.0	460	11	-1.0	12.66	0.66	12.17	0.17	11.02	-0.97	11.01	-0.98
23.0	18	18	-5.0	26.84	3.84	28.22	5.22	28.32	5.32	29.78	6.78
20.8	152	16	-4.8	20.09	-0.70	20.25	-0.54	19.29	-1.50	19.21	-1.58
14.0	219	14	0.0	16.35	2.35	15.85	1.85	15.95	1.95	15.44	1.44
18.2	122	16	-2.2	17.45	-0.74	17.51	-0.68	17.99	-0.20	17.96	-0.23
15.0	177	16	1.0	15.39	0.39	15.12	0.12	16.28	1.28	16.01	1.01
15.1	253	16	0.9	11.91	-3.19	12.11	-2.98	12.03	-3.06	12.23	-2.86
12.9	405	9	-3.9	15.03	2.13	15.39	2.49	14.79	1.89	15.17	2.27
17.0	275	9	-8.0	18.99	1.99	20.00	3.00	18.29	1.29	19.15	2.15
15.6	380	9	-6.6	15.72	0.12	16.02	0.42	14.80	-0.79	15.21	-0.38
15.3	395	8	-7.3	14.40	-0.89	13.72	-1.57	13.97	-1.32	12.91	-2.38
18.0	410	11	-7.0	15.44	-2.55	15.45	-2.54	14.63	-3.37	14.87	-3.12
13.8	435	9	-4.8	13.08	-0.71	13.03	-0.76	11.96	-1.83	12.01	-1.78
16.0	370	11	-5.0	15.12	-0.87	15.62	-0.37	14.51	-1.48	14.79	-1.21
15.8	415	9	-6.8	12.63	-3.16	13.10	-2.69	12.09	-3.70	12.25	-3.54
12.0	445	9	-3.0	13.37	1.37	13.14	1.14	12.00	0.00	12.11	0.11

Codes :

ACT GYC	Actual GYC
ELE	Elevation
BUS	Value predicted by Busby (1974)
MODEL 52,..56	Values predicted by models 52, 53, 55, 56
DIFF	Difference predicted - actual GYC

APPENDIX 9

USE OF DUMMY VARIABLES.

Dummy (or indicator) variables provide a convenient method of estimating the effects of qualitative variables in regression analysis. Dummy variables are created by treating each category of a qualitative variable (eg. soil type) as a separate variable and assigning a "score" for each case depending on its presence or absence (usually one for presence and zero for absence).

For example, suppose one wishes to investigate the influence several quantitative factors X_1 - X_n and a qualitative factor K, which has three categories k1, k2 and k3, on a dependant variable Y. The data matrix would appear as below with three columns for the factor K, one for each of the categories k1-k3. These columns are termed a "set of dummy variables". For each observation (row) the values in each of the three columns for the dummy variables are set at one (if the observation belongs to that class) or zero (if it does not belong to that class).

Y	X_1	X_2 ...	X_n	K		
				C1	C2	C3
y_1	X_{11}	X_{21}	X_{n1}	1	0	0
y_2	X_{12}	X_{22}	X_{n2}	1	0	0
y_3	X_{13}	X_{23}	X_{n3}	0	1	0
y_4	X_{14}	X_{24}	X_{n4}	0	0	1
y_5	X_{15}	X_{25}	X_{n5}	1	0	0

Observations 1, 2 and 5 belong to class k1, observation 3 belongs to class k2 and observation 4 belongs to class k3. The dummy variables (ie. columns C1 - C3) now in effect contain metric (quantitative) values and can be included in a regression analysis on the same basis as any other quantitative variable. The only main difference is that because the values of the k'th dummy variable are completely determined by the preceding k-1 dummy variables, one of the categories has to be excluded to allow solution of the normal equations. The excluded variable becomes a sort of reference point ("reference category") and in the derived regression equation the effects of the other variables are expressed relative to this category.

For the example above, with k3 treated as the reference category, the equation would appear as above:

$$Y = a + b_1X_1 + b_2X_2 + b_nX_n + c_1\{K1\} + c_2\{K2\}$$

The terms c_1 and c_2 are coefficients which express the effect of the observations belonging in categories k1 and k2 relative to category k3. Their values are arrived at by the least squares method in exactly the same way as the coefficients for the quantitative variables ($b_1 - b_n$). The values of K1 and K2 are either 1 or zero depending on the which category the equation is to apply to. To make a prediction for category k1, K1 is set to 1 (one) and K2 to 0 (zero). This means that the term $c_1\{K1\}$ becomes the numerical value for c_1 and $c_2\{K2\}$ disappears. To make a prediction for category k2, K2 is set to 1 (one) and K1 to zero so as the term $c_1\{K1\}$ disappears. To make a prediction for k3, both K1 and K2 are set to zero and both the K-terms disappear. Testing the significance of a categorical variable is done by adding the contribution to the sums of squares attributable to each category, dividing by the degrees of freedom (number of categories minus one) and comparing this with the root mean of the model. Any number of categorical variables can be included in a regression analysis using dummy variables, but it should be remembered that each category is associated with a degree of freedom.

Appendix 10. Windzone map